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Complete List of Authors:	Meikle, Brandon; Queensland Children's Hospital, Centre for Children's Burns and Trauma Research; The University of Queensland Faculty of Medicine, Children's Health Research Centre Simons, Megan; Queensland Children's Hospital, Occupational Therapy; The University of Queensland, Children's Health Research Centre Mahoney, Tamsin; Metro North Hospital and Health Service, Surgical, Treatment and Rehabilitation Services (STARS) Reddan, Tristan; Children's Health Queensland Hospital and Health Service, Medical Imaging and Nuclear Medicine; Queensland University of Technology, School of Clinical Sciences, Faculty of Health Dai, Bryan; The University of Queensland Kimble, Roy; Children's Health Queensland Hospital and Health Service, Pegg Leditschke Children's Burns Centre; The University of Queensland, Faculty of Medicine Tyack, Zephanie; The University of Queensland, Children's Health Research Centre, Faculty of Medicine; Queensland University of Technology, Australian Centre for Health Service Innovation (AusHI), Centre for Healthcare Transformation, and School of Public Health and Social Work
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Ultrasound measurement of traumatic scar and skin thickness: A scoping review of evidence across the translational pipeline of research-to-practice*

Running Title: Review of scar thickness measurement with ultrasound

Brandon Meikle[1,2**], Megan Simons[2,3,7], Tamsin Mahoney[4], Tristan Reddan[5,6], Bryan Dai[2], Roy M Kimble[1,2,6,7] and Zephanie Tyack[2,8]

[1] Centre for Children's Burns and Trauma Research, Queensland Children's Hospital, Brisbane, Queensland, Australia

[2] Children's Health Research Centre, Faculty of Medicine, The University of Queensland, Herston, Queensland, Australia

[3] Occupational Therapy Department, Queensland Children's Hospital, Children's Health Queensland Hospital and Health Service, Brisbane, Queensland, Australia

[4] Surgical, Treatment and Rehabilitation Services (STARS), Metro North Hospital and Health Service, Brisbane, Queensland, Australia

[5] Medical Imaging and Nuclear Medicine, Queensland Children's Hospital and Health Service, Brisbane, Queensland, Australia

[6] School of Clinical Sciences, Faculty of Health, Queensland University of Technology, Brisbane, Queensland, Australia

[7] Pegg Leditschke Children's Burns Centre, Queensland Children's Hospital, Children's Health Queensland Hospital and Health Service, Brisbane, Queensland, Australia

[8] Australian Centre for Health Service Innovation (AusHI), Centre for Healthcare Transformation, and School of Public Health and Social Work, Queensland University of Technology, Brisbane, Queensland, Australia

** Corresponding author

E-mail: brandon.meikle@uq.net.au (BM)

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ABSTRACT:

Objectives: To identify the ultrasound methods used in the literature to measure traumatic scar thickness, and map gaps in the translation of these methods using evidence across the research-to-practice pipeline.

Design: Scoping review

Data Sources: Electronic database searches of Ovid MEDLINE, Embase, Cumulative Index of Nursing and Allied Health Literature (CINAHL) and Web of Science. Grey literature searches were conducted in Google. Searches were conducted from inception (date last searched 27/05/2022).

Data Extraction: Records using B-mode ultrasound to measure scar and skin thickness across the research-to-practice pipeline of evidence were included. Data was extracted from included records pertaining to: methods used; reliability and measurement error; clinical, health service, implementation and feasibility outcomes; factors influencing measurement methods; strengths and limitations; and use of measurement guidelines and/or frameworks.

Results: Of the 9309 records identified, 118 were included for analysis (n = 82 journal articles, n = 36 abstracts) encompassing 5213 participants. Reporting of methods used was poor. B-mode, including high-frequency (i.e., > 20 MHz) ultrasound was the most common type of ultrasound used (n = 72; 61%), and measurement of the combined epidermal and dermal thickness (n = 28; 24%) was more commonly measured than the epidermis or dermis alone (n = 7, 6%). The scar characteristics most commonly reported to be measured were epidermal oedema, and dermal fibrosis and hair follicle density. Most records analysed (n = 115; 97%) pertained to the early stages of the research-to-practice pipeline, as part of research initiatives.

Conclusions: The lack of evaluation of measurement initiatives in routine clinical practice was identified as an evidence gap. Considerations for the ultrasound measurement of cutaneous traumatic scarring in research and clinical practice are presented based on the review findings. Standardising the core methodological components of ultrasound measurement is recommended based on poor methodological reporting in some records.

STRENGTHS AND LIMITATIONS OF THIS STUDY:

- Evidence pertaining to the implementation of ultrasound measurement in routine clinical practice and research-to-practice gaps were determined by categorising included records into one of the four Australian Government Department of Health and Aged Care Medical Research Future Fund research-to-practice pipeline phases.
- Clinical, health service, implementation and feasibility outcomes related to ultrasound measurement in included records were summarised to determine what is needed to close the research-to-practice gap for ultrasound measurement of scar thickness.
- The reported methods compiled in this review were used to inform the development of nine methodological considerations to guide health practitioners and researchers using ultrasound to measure scar and skin thickness.
- A limitation is that only articles available in English or with an English abstract were considered for inclusion and data extraction, although the large number of included records means this is unlikely to have changed the review findings.

INTRODUCTION:

Traumatic cutaneous injury, caused by sharp object penetration (e.g., surgery or vaccination) or burns (including thermal, chemical and friction) may result in the formation of hypertrophic scarring. [1] While major injuries to non-fetal skin heal through the formation of scar tissue, most resultant scars are small, linear and/or barely visible. [2-5] Hypertrophic scars, however, result from an aberrant healing response that leads to the formation of red, raised scars, often accompanied by pruritus and skin tightening, which remain within the boundaries of the initial injury. [6-11] The sequelae of hypertrophic scars have the potential to impact patient's physical and psychosocial quality of life. [12 13]

A characteristic of hypertrophic scarring that both patients and clinicians have identified as being important, and which has subsequently been used as a way to measure clinical and treatment outcomes, is scar thickness. [13-21] Scar thickness can be measured both subjectively, through clinician assessment and patient-reported outcomes, or objectively, utilising medical imaging methods. [22 23] The pathological complexity of hypertrophic scars means that they generally extend below the level of the surrounding skin, supporting the use of medical imaging modalities such as ultrasound for thickness quantification, as these are capable of providing information about subcutaneous structures and processes. [23 24] Scar thickness measurement using ultrasound can be conducted in both clinical and research contexts. For example, ultrasound is regularly used in our own clinical practice at the Pegg Leditschke Children's Burn Centre to measure scar thickness, [25] particularly prior to treatment with ablative fractional CO_2 laser, where scar thickness measurement is used to determine the required depth of penetration. [26] The routine use of measurements like ultrasound to guide clinical decision-making has been termed measurement-based care. [27]

There are several clinical skills that assessors or practitioners are required to master to effectively conduct measurement of scar thickness with ultrasound. Proficiency in these skills may aid in bridging the gap between its use predominantly in research methods, to more widespread use in routine clinical practice. These skills have previously been described as part of a training curriculum in point-of-care ultrasound, [28] but can equally be applied to scar thickness measurement using ultrasound. These include: 1) understanding when to conduct scar thickness measurement with ultrasound; 2) the ability to operate an ultrasound machine to obtain useful images; 3) the ability to recognise physiological and pathological skin features (i.e., epidermis, dermis) on ultrasound images, and be able to measure the thickness of each; and 4) successfully utilising the thickness measurement as the basis of measurement-based care, including quantifying changes in scar thickness in response to treatment. [28] For example, a study of ultrasound measurement in people with systematic sclerosis identified that ultrasound may be capable of differentiating between early oedema and fibrosis, and detect thickening before it is observed clinically, thus providing opportunities to prevent or treat fibrosis early. [29] Whilst it is ideal for all ultrasound assessors to have the skills mentioned, the number of assessors required to be proficient in these skills differs in research and clinical practice. In research, a small number of researchers are generally responsible for conducting ultrasound measurement, whereas members across the entire multi-disciplinary team may be required to conduct these measurements in routine clinical practice, and thus require some level of proficiency. [30]

Ultrasound, itself, is a popular, safe, non-invasive and largely cost-effective (compared to other imaging modalities) imaging method with measurement utility in both adult and paediatric populations. [25 31 32] Modern B-mode (brightness mode) ultrasound, particularly high- (i.e., ≥20 MHz) or ultra-high frequency (30-100 MHz) [33] ultrasonography, has the capacity to allow differentiation between the epidermis and dermis, permitting quantification of skin layer-specific scar characteristics. This allows assessors to observe and understand the pathological mechanisms of individual scars and adjust treatment protocols accordingly. [25 34-

[39] Indeed, measurement of scar thickness using these methods may allow quantification of fibrosis and oedema within the scar, and can also be used to distinguish scar tissue from uninjured skin by measuring the presence and density of hair follicles. [40-43] B-mode ultrasound is also commonly used as the basis for other imaging methods, such as colour Doppler ultrasound or elastography, which can allow quantification of additional scar characteristics, such as their elastic properties. [34-37 44 45]

Despite the clinical advantages of B-mode ultrasound for scar thickness measurement, methods utilised in the literature are poorly reported and lack standardisation. This casts doubt on the validity of clinical decision-making in measurement-based care initiatives (e.g., setting depth of AFCO$_2$ penetration) informed by research findings (e.g., response to treatment) where ultrasound measurements are used. [46] Lack of standardisation also makes between-study comparison, such as systematic reviews and meta-analyses, difficult, [47] and poor methodological reporting hampers the ability to accurately replicate findings. This scoping review focusses on mapping and identifying gaps in ultrasound methods and evaluation reported in the current literature along the research-to-clinical practice pipeline. Methodological considerations for assessors or practitioners performing scar thickness measurements using ultrasound are presented based on the review findings.

METHODS:

Protocol Publication and Review Structure:

The protocol for this review has been published *a priori*. [48] This scoping review was conducted and is reported according to the Arksey and O'Malley (2005) [49] framework. The steps outlined in this framework are: 1) identifying the research question; 2) identifying relevant records; 3) selecting appropriate records; 4) charting extracted data; and 5) collating, summarising and reporting the results. [49]

Research Question:

The primary question of this scoping review was: “What do we know and not know about the measurement of traumatic cutaneous scar thickness using ultrasound?” This question was addressed through exploration of: methods used; reliability and measurement error; clinical, health service, implementation and feasibility outcomes; factors influencing ultrasound imaging and measurement methods; strengths and limitations of measurement methods; and use of measurement guidelines and/or frameworks. While the focus of this review was the measurement of traumatic cutaneous scar thickness with ultrasound, methods used to measure the thickness of unscarred skin were reported where these were used in combination with measurement of scar thickness (e.g., as control or comparator measurements).

Identifying Relevant Records:

A standardised search strategy was developed and piloted with the assistance of a medical librarian using the concepts ‘ultrasound’, ‘skin’, ‘thickness’ and ‘measure’, with associated terms and truncations (supplementary box 1). Ovid MEDLINE, Embase, Cumulative Index of Nursing and Allied Health Literature (CINAHL) and Web of Science electronic databases were searched from conception to identify original studies (date last searched 27th May 2022).

The phrase ‘ultrasound scar thickness measurement’ was used to conduct additional searches in 1) Google Scholar, and 2) Google to identify original studies in grey literature, and studies not identified in database searches. Title and abstract searches in Google Scholar and Google were limited to the first 200 results. [50]

Record Selection:

Following de-duplication, six reviewers screened records using Covidence (Veritas Health Innovation, Melbourne, Australia; available at www.covidence.org) for eligibility according to the inclusion criteria (Table 1). During both title and abstract and full text screening, one researcher (BM) screened all records as a single reviewer, while other researchers (MS, TM, TR, BD and ZT) screened records as a second reviewer. Conflicts were resolved through discussion between at least two authors to reach agreement. A third author was used as a tiebreaker where agreement could not be reached.

Table 1. Inclusion and exclusion criteria for studies included in the scoping review.

Inclusion	Exclusion
• Traumatic scars measured with ultrasound based on B-mode ultrasound (including high-frequency, ultra-high-frequency and Doppler) • Measurements taken of living, human individuals • Measurement of traumatic cutaneous scarring arising from penetration of the skin with sharp objects (including surgery or vaccination), or as a result of burns, (including thermal, chemical or friction) • Articles written in English, or with English abstracts	• Reviews, discussion papers, opinion pieces • Measurement of non-traumatic scars (e.g., acne scars) • Measurement of skin thickness in non-traumatic conditions (e.g., diabetes) • Measurement of skin thickness where there is no cutaneous involvement in the trauma (e.g., traumatic brain injury) • Measurement using A-mode ultrasound

Charting the Data:

The data extraction table was developed in Microsoft Excel and piloted by two authors (BM and ZT) through independent extraction and comparison of data from two records. The table was then modified to include the scar characteristics (e.g., fibrosis, oedema) measured, measurer/assessor training, and the number of measurements taken (Supplementary Table 1). Full text data extraction was completed by four authors (BM, MS, TM and ZT). An additional author (BD) independently extracted data from five randomly selected records, which was compared to data extracted by other authors. Minimal differences between data extracted by the independent author and that by other authors were observed, thus further independent extraction was not performed. As is typical in scoping reviews, the certainty or quality of evidence was not appraised. [49]

The research-to-practice pipeline published by the Australian Government Department of Health and Aged Care Medical Research Future Fund (figure 1) was used to categorise each included record based on their stated aims into one of the four phases. [51] The final phase of this pipeline (phase 4) indicates initiatives used in routine clinical practice.

Where clinical (e.g., treatment satisfaction, scar symptoms), health service (e.g., efficiency, safety, effectiveness, equity, patient-centredness and timeliness) and implementation (e.g., acceptability, adoption, appropriateness, fidelity, cost, penetration and sustainability) outcomes were addressed, they were reported according to Proctor *et al.* [52]. Measurement instrument-specific feasibility outcomes defined by Prinsen *et al.* [53] are reported in the current review. These outcomes included ease of administration, standardisation, completion time, instrument cost and availability, and ease of score calculation. [53] Reliability and measurement error were defined according to COnsensus-based Standards for the selection of health Measurement INstruments (COSMIN) tools. [54 55] Measurements with an intraclass correlation coefficient (ICC) of 0.7 or greater were considered reliable. [55] Measurement error was assessed by comparing the reported standard error of the measurement (SEM) with the reported smallest detectable change (SDC). Where the reported measurement error was smaller than the reported smallest detectable change, it was interpreted as indicating real change or variance can be detected, and that change or variance is not a result of error. [55]

Patient and Public Involvement

There was no patient and/or public involvement in the design, conduct, reporting or dissemination of information in this scoping review.

RESULTS:

Electronic database searches identified 9309 records. After removal of 3703 duplicate records, the titles and abstracts of 5606 records were screened for relevance according to the inclusion criteria (Table 1). Following full-text screening, 104 records proceeded to data extraction. Searches in Google and Google Scholar identified an additional 14 records, providing a total of 118 records for data extraction. Search and screening results are presented according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram (figure 2). [56]

Record Characteristics:

Of the 118 records included in this review, 82 were journal articles (69%) and 36 were abstracts (31%) (Table 2), representing a total of 5213 participants. The majority (n = 44; 37% of included records) measured adults aged 8 years or older, [21,26,34,36-38,42,43,57-94] and were measurements of burn scars (n = 69 records; 58%) (Table 2). [21,25,26,31,32,35,36,38,42,59,64,66-71,74-78,84-87,91,92,94-133] Most identified records used ultrasound measurement of scar thickness as part of research initiatives, and were categorised as either phase 2 (n= 70; 59%)[21,31,34,39,42,43,57,59-63,66,67,69,70,73,74,77-80,83,84,87-90,92,93,95-98,100-102,105-107,113,116-122,124-126,128,133-151] or phase 3 (n = 45; 38%)[25,26,32,35-38,58,64,65,68,71,72,75,76,81,82,85,86,91,94,103,108,110-112,114,115,123,127,129-132,152-161] on the research-to-practice pipeline. [51] Three records (3%)[99,104,109] used ultrasound to measure treatment response to an intervention already used in routine clinical practice (phase 4), including compression garments[99,109] and CO_2 fractional laser. [104]

Table 2. Characteristics of records included in this review

First Author (year)	Sample Size (n)	Population Type	Scar Aetiology	Translational Pipeline Phase*
Journal articles				
Agabalyan (2017)	10	Adult	Not specified	2
Alsharnoubi (2018)	15	Paediatric	Burn	2
Alsharnoubi (2018)	15	Paediatric	Burn	2
Alshehari (2015)	30	Not reported	Mixed	2

Avetikov (2018)	50	Paediatric & adult	Not specified	3
Berry (1985)	16	Paediatric & adult	Burn	4
Blome-Eberwein (2012)	16	Paediatric & adult	Burn	2
Blome-Eberwein (2016)	36	Adult	Not specified	2
Blome-Eberwein (2019)	19	Adult	Burn	2
Cai (2019)	51	Adult	Not specified	2
Candy (2010)	17	Adult	Not specified	2
Chae (2016)	23	Adult	Not specified	3
Chang (2014)	60	Adult	Surgical	2
Chan (2004)	56	Paediatric & adult	Burn	2
Cheng (2001)	58	Paediatric	Burn	3
Cho (2014)	146	Not reported	Burn	2
Danin (2012)	22	Paediatric & adult	Burn	3
Deng (2019)	20	Adult	Not specified	2
Deng (2021)	31	Adult	Not specified	2
Deng (2021)	45	Adult	Not specified	2
Dunkin (2007)	113	Adult	Surgical	2
Elrefaie (2020)	22	Paediatric & adult	Not specified	2
Engrav (2010)	67	Paediatric & adult	Burn	4
Fabbrocini (2016)	20	Adult	Mixed	2
Fong (1997)	16	Paediatric & adult	Burn	3
Fraccalvieri (2013)	3	Paediatric & adult	Mixed	2
Fraccalvieri (2011)	5	Adult	Mixed	2
Gankande (2014)	30	Adult	Burn	3
Ge (2022)	21	Paediatric & adult	Mixed	3
Gee Kee (2016)	43	Paediatric	Burn	2
Guo (2020)	87	Paediatric & adult	Not specified	3
Huang (2017)	1	Adult	Burn	3
Huang (2021)	5	Adult	Burn	3
Huang (2020)	43	Adult	Not specified	3
Issler-Fisher (2021)	187	Adult	Burn	2
Issler-Fisher (2020)	78	Adult	Burn	3
Issler-Fisher (2017)	47	Paediatric & adult	Burn	3
Joo (2020)	48	Adult	Not specified	2
Katz (1985)	4	Not reported	Burn	3
Kemp Bohan (2021)	21	Not reported	Burn	3

Kim (2018)	148	Not reported	Burn	3
Lacarrubba (2008)	8	Paediatric & adult	Mixed	2
Lau (2005)	100	Paediatric & adult	Burn	2
Lee (2020)	55	Adult	Burn	2
Lee (2019)	55	Adult	Burn	2
Li (2013)	7	Adult	Burn	2
Li (2020)	21	Paediatric & adult	Mixed	2
Li (2021)	165	Paediatric	Mixed	2
Li (2018)	34	Adult	Burn	3
Li (2021)	105	Adult	Burn	2
Li-Tsang (2005)	101	Adult	Surgical	3
Li-Tsang (2006)	45	Adult	Not specified	2
Li-Tsang (2010)	104	Paediatric & adult	Mixed	2
Lobos (2017)	35	Paediatric & adult	Not specified	3
Mamdouh (2021)	40	Adult	Not specified	2
Meirte (2016)	9	Adult	Burn	2
Miletta (2021)	29	Paediatric & adult	Burn	2
Nedelec (2014)	46	Adult	Burn	3
Nedelec (2008)	32	Adult	Burn	3
Nedelec (2019)	70	Adult	Burn	2
Nedelec (2020)	51	Adult	Burn	2
Nicoletti (2015)	27	Paediatric & adult	Surgical	2
Niessen (1998)	145	Paediatric & adult	Surgical	2
Reinholz (2020)	25	Adult	Mixed	2
Reinholz (2016)	8	Adult	Not specified	3
Schwaiger (2018)	15	Adult	Mixed	2
Simons (2017)	49	Paediatric	Burn	3
Soykan (2014)	87	Adult	Surgical	3
Timar-Banu (2011)	30	Adult	Mixed	3
Ud-Din (2019)	62	Adult	Not specified	3
van den Kerckhove (2005)	60	Adult	Burn	2
van den Kerckhove (2003)	6	Adult	Burn	3
van der Veer (2010)	44	Adult	Surgical	2
Wang (2009)	22	Adult	Burn	2
Wang (2010)	21	Paediatric	Burn	3
Wiseman (2020, 2021)	153	Paediatric	Burn	2
Wood (1996)	1	Paediatric	Burn	3
Xuan (2021)	72	Not reported	Not specified	2
Yeol Lee (2022)	16	Adult	Mixed	3
Yim (2010)	31	Paediatric & adult	Burn	2
Zadkowski (2016)	47	Paediatric	Burn	2

Abstracts				
Agabalyan (2016)	10	Not reported	Burn	2
Anthonissen (2015)	N.R.	Not reported	Burn	3
Bajouri (2018)	20	Not reported	Burn	2
Bezugly (2019)	438	Not reported	Not specified	3
Bezugly (2014)	103	Not reported	Mixed	3
Blome-Eberwein (2011, 2012)	16	Paediatric & adult	Mixed	2
Blome-Eberwein (2012)	19	Adult	Burn	3
Blome-Eberwein (2014)	66	Not reported	Burn	2
Cho (2012)	30	Not reported	Burn	4
Cho (2012)	60	Paediatric & adult	Burn	2
Comstock (2018)	1	Adult	Burn	2
Cooper (2021)	25	Not reported	Burn	2
Du (2006)	1	Adult	Burn	3
Edgar-Lacoursière (2022)	44	Not reported	Burn	3
El-Zawhary (2007)	57	Not reported	Mixed	2
George (2019)	11	Not reported	Burn	3
Jacobs (2016)	6	Paediatric & adult	Burn	2
Jang (2009)	20	Not reported	Not specified	2
Kim (2009)	5	Paediatric & adult	Burn	2
Li (2016)	34	Not reported	Burn	3
Li-Tsang (2011)	4	Not reported	Not specified	2
Li-Tsang (2010)	45	Not reported	Not specified	2
Maari (2017)	12	Not reported	Not specified	2
Moortgat (2020)	10	Not reported	Burn	2
Nedelec (2018)	60	Not reported	Burn	2
Peters (2018)	5	Not reported	Burn	2
Seo (2011)	48	Not reported	Burn	3
Siwy (2016)	15	Not reported	Burn	2
Timina (2013)	49	Not reported	Not specified	3
Tu (2014)	59	Not reported	Not specified	2
Ud-Din (2017)	20	Not reported	Surgical	2
Ud-Din (2017)	20	Not reported	Surgical	3
Ud-Din (2018)	62	Not reported	Surgical	3
Zuccaro (2021)	20	Paediatric	Burn	3
Zuccaro (2019)	13	Paediatric	Burn	3
Zuccaro (2021)	20	Paediatric	Burn	3

Legend: Paediatric: measurement of patients under the age of 18; Adult: measurement of patients aged 18 years or older; N.R.: Not reported; Burn: scars caused by thermal,

chemical or friction injury; Surgical: scars caused by surgical procedures (including biopsies); Mixed: participant scars caused by mixed trauma (e.g., burn and acne)
Footnotes: *Stage in the research to clinical practice translational pipeline, based on the Australian Government Department of Health and Aged Care[51]

Methods used to measure traumatic cutaneous scar thickness:

B-mode, including high-frequency (i.e., ≥ 20 MHz) B-mode ultrasound was the most commonly reported ultrasound type (n = 72; 61%) (Table 3). Specialised B-mode ultrasound devices, including the Tissue Ultrasound Palpation System (TUPS; a B-mode ultrasound transducer in-series with a load cell to allow measured compression of the skin), [72 117 141 144] and colour Doppler ultrasound, [61 156] were used in six records (Table 3).

Table 3. Measurement methods used in included records.

First Author (year)	Ultrasound Type	Ultrasound Frequency (MHz)	Measurement Parameters	Scar Characteristic Measured	Scar Relocation
Journal articles					
Agabalyan (2017)	High-frequency	20	Epidermal, dermal & combined	N.R.	Not relevant – single measurement
Alsharnoubi (2018)	Midrange ultrasound	N.R.	N.R.	Fibrosis	N.R.
Alsharnoubi (2018)	Midrange ultrasound	N.R.	N.R.	Fibrosis[†]	N.R.
Alshehari (2015)	N.R.	N.R.	Maximum elevation above normal skin	N.R.	N.R.
Avetikov (2018)	B-mode	N.R.	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Berry (1985)	N.R.	N.R.	N.R.	N.R.	N.R.[‡]
Blome-Eberwein (2012)	B-mode	N.R.	Combined epidermal & dermal[§]	N.R.	N.R.[‡]
Blome-Eberwein (2016)	High-frequency	50	N.R.	Fibrosis[†]	N.R.[‡]
Blome-Eberwein (2019)	High-frequency	35	Dermal	Fibrosis, hair follicle density	N.R.
Cai (2019)	High-frequency	50	Dermal	N.R.	N.R.[‡]
Candy (2010)	B-mode	N.R.	N.R.	N.R.	Scar boundaries traced
Chae (2016)	N.R.	N.R	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Chang (2014)	N.R.	12	N.R.	N.R.	N.R.

Chan (2004)	N.R.	N.R.	N.R.	N.R.	Tracing
Cheng (2001)	B-mode	5-10	Combined epidermal & dermal	N.R.	Tracing & cutting out paper Photographs
Cho (2014)	High-frequency	7.5	N.R.	N.R.	N.R.
Danin (2012)	B-mode	20	Epidermal & dermal	N.R.	N.R.
Deng (2019)	N.R.	N.R.	N.R.	N.R.	N.R.
Deng (2021)	Colour Doppler	4-15	Dermal	Fibrosis[†]	N.R.
Deng (2021)	B-mode	8-12	Epidermal & dermal	Fibrosis[†]	Photographs
Dunkin (2007)	High-frequency	N.R.	N.R.	Fibrosis & oedema[†]	Measurements taken at set linear distances along scar
Elrefaie (2020)	High-frequency	13	N.R.	Fibrosis & oedema[†]	N.R[‡]
Engrav (2010)	N.R.	N.R.	N.R.	N.R.	N.R.
Fabbrocini (2016)	N.R.	N.R.	N.R.	Fibrosis & oedema[†]	N.R[‡]
Fong (1997)	B-mode	7.5	N.R.	Fibrosis[†]	Tracing
Fraccalvieri (2013)	High-frequency	7-10 & 10-13	N.R.	Fibrosis & oedema[†]	N.R.
Fraccalvieri (2011)	High-frequency	10-13	Combined epidermal & dermal	Fibrosis[†]	N.R.
Gankande (2014)	High-frequency	20	Combined epidermal & dermal	N.R.	Scar marked & photographed
Ge (2022)	N.R.	N.R.	N.R.	N.R.	N.R.
Gee Kee (2016)	B-mode	8-18	Combined epidermal & dermal	N.R.	Transducer in centre of original burn site where no scar present
Guo (2020)	N.R.	2-15 & 4-15	Combined epidermal & dermal[c]	Fibrosis[†]	Thickest site on peripheral regions
Huang (2017)	N.R.	N.R.	Combined epidermal & dermal	N.R.	Marked & linear measurements from bony landmarks

Huang (2021)	B-mode	5-12	N.R.	Oedema[†]	Not relevant – single measurement
Huang (2020)	B-mode	5-12	Combined epidermal & dermal	N.R.	N.R.
Issler-Fisher (2021)	N.R.	N.R.	N.R.	N.R.	Photograph & measurement of thickest area
Issler-Fisher (2020)	N.R.	N.R.	N.R.	N.R.	N.R.
Issler-Fisher (2017)	N.R.	N.R.	N.R.	Fibrosis[†]	Scar mapped with drawing Thickest area measured
Joo (2020)	N.R.	N.R.	N.R.	Fibrosis[†]	N.R.
Katz (1985)	B-mode	10	Combined epidermal & dermal	N.R.	N.R.
Kemp Bohan (2021)	High-frequency	12	N.R.	Fibrosis[†]	Tracing – thickest area & adjacent landmarks marked
Kim (2018)	N.R.	22	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Lacarrubba (2008)	B-mode	20	Combined epidermal & dermal	N.R.	N.R.
Lau (2005)	Tissue Ultrasound Palpation System	5 (burn) & 10 (surgical)	N.R.	N.R.	Tracing – most severe/prominent site
Lee (2020)	High-frequency	20	Combined epidermal & dermal	Fibrosis[†]	Not relevant – single measurement
Lee (2019)	High-frequency	20	Combined epidermal & dermal	Fibrosis[†]	Marked with pen
Li (2013)	High-frequency	12	Combined epidermal & dermal	Fibrosis[†]	Tracing
Li (2020)	N.R.	10	N.R.	Fibrosis[†]	N.R.
Li (2021)	High-frequency	20	N.R.	N.R.	Thickest area
Li (2021)	High-frequency	20	N.R.[§]	Fibrosis[†]	Thickest area
Li (2018)	N.R.	N.R.	Combined epidermal & dermal	N.R.	N.R.
Li-Tsang (2005)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2006)	B-mode	N.R.	N.R.	N.R.	N.R[‡]

Li-Tsang (2010)	B-mode	N.R.	N.R.	Fibrosis†	N.R.
Lobos (2017)	B-mode & colour Doppler	18	N.R.	Fibrosis†	Not relevant – single measurement
Mamdouh (2021)	High-frequency	N.R.	Combined epidermal & dermal§	Fibrosis†	N.R.
Meirte (2016)	High-frequency	22	Dermal	Fibrosis & oedema†	Marked with surgical pen, including boundaries of probe. Photograph of body position & probe location
Miletta (2021)	N.R.	50	N.R.	Fibrosis†	Tracing – worst scar
Nedelec (2014)	High-frequency	20	Combined epidermal & dermal	N.R.	Tracing including notable landmarks. Measurement site circled. Photograph
Nedelec (2008)	High-frequency	20	Combined epidermal & dermal	N.R.	Tracing including notable landmarks. Measurement site circled. Photograph
Nedelec (2019)	High-frequency	20	Combined epidermal & dermal	Fibrosis & oedema†	Tracing. Hole cut over measurement area
Nedelec (2020)	High-frequency	20	Combined epidermal & dermal	N.R.	Photograph
Nicoletti (2015)	N.R.	22	Epidermis to fascia	N.R.	N.R.
Niessen (1998)	B-mode	N.R.	N.R.	Fibrosis & oedema†	3cm border marked with tape – measurements lateral
Reinholz (2020)	B-mode	11	Combined epidermal & dermal	Fibrosis & oedema†	N.R.
Reinholz (2016)	B-mode	11	Combined epidermal & dermal§	Fibrosis & oedema†	N.R.
Schwaiger (2018)	B-mode	11	N.R.	Fibrosis & oedema†	N.R.
Simons (2017)	B-mode	8-18	Combined epidermal & dermal	N.R.	Tracing – scar & anatomical landmarks

Soykan (2014)	N.R.	3-9	N.R.	Fibrosis[†]	N.R.
Timar-Banu (2001)	High-frequency	20	Combined epidermal & dermal	Fibrosis[†]	N.R.
Ud-Din (2019)	High-frequency	50	Combined epidermal & dermal	Fibrosis	Defined anatomical location
van den Kerckhove (2003)	High-frequency	20	Combined epidermal & dermal	N.R.	Test sites marked. Thermoplastic splints created with space for transducer
van den Kerckhove (2005)	High-frequency	20	Combined epidermal & dermal	N.R.	Test site boundaries marked & traced
van der Veer (2010)	N.R.	7.5	N.R.	Fibrosis[†]	Standardised linear measurement points
Wang (2009)	High-frequency	N.R.	N.R.	Fibrosis[†]	N.R.
Wang (2010)	B-mode	N.R.	Combined epidermal & dermal	N.R.	Tracing – scar & anatomical landmarks
Wiseman (2020, 2021)	B-mode	N.R.	Combined epidermal & dermal	Fibrosis[†]	Centrally site of interest
Wood (1996)	B-mode	7 & 10	N.R.	N.R.	Transducer affixed to tracking arm
Xuan (2021)	High-frequency	20	N.R.	Fibrosis[†]	N.R.
Yeol Lee (2022)	B-mode	7-16	N.R.	N.R.	N.R.
Yim (2010)	High-frequency	12	N.R.	N.R.	N.R.
Zadkowski (2016)	B-mode	N.R.	Combined epidermal & dermal	N.R.	N.R.
Abstracts					
Agabalyan (2016)	N.R.	20	Epidermal, dermal & combined	N.R.	N.R.
Anthonissen (2015)	N.R.	22	Epidermal & dermal	N.R.	N.R.
Bajouri (2018)	N.R.	N.R.	Epidermal & dermal	N.R.	N.R.

Bezugly (2019)	High-frequency	22, 33 & 75	Epidermal & dermal	N.R.	N.R.
Bezugly (2014)	High-frequency	33 & 75	Epidermal & dermal	N.R.	N.R.
Blome-Eberwein (2011, 2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Blome-Eberwein (2012)	High-frequency	N.R.	N.R.	Fibrosis	N.R.
Blome-Eberwein (2014)	High-frequency	N.R.	N.R.	N.R.	N.R.
Cho (2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Cho (2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Comstock (2018)	N.R.	N.R.	N.R.	N.R.	N.R.
Cooper (2021)	N.R.	N.R.	N.R.	N.R.	N.R.
Du (2006)	B-mode	15	N.R.	N.R.	N.R.
Edgar-Lacoursière (2022)	N.R.	N.R.	N.R.	N.R.	N.R.
El-Zawhary (2007)	N.R.	N.R.	N.R.	N.R.	N.R.
George (2019)	N.R.	N.R.	N.R.	N.R.	N.R.
Jacobs (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Jang (2009)	N.R.	N.R.	N.R.	N.R.	N.R.
Kim (2009)	N.R.	N.R.	N.R.	N.R.	N.R.
Li (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2011)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2010)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Maari (2017)	N.R.	N.R.	N.R.	N.R.	N.R.

Moortgat (2020)	High-frequency	N.R.	Dermal	N.R.	N.R.
Nedelec (2018)	N.R.	N.R.	N.R.	N.R.	N.R.
Peters (2018)	High-frequency	22	N.R.	N.R.	N.R.
Seo (2011)	N.R.	7.5	N.R.	N.R.	Thickest point
Siwy (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Timina (2013)	N.R.	20-40	N.R.	N.R.	N.R.
Tu (2014)	High-frequency ultrasound biomicroscopy	N.R.	N.R.	N.R.	N.R.
Ud-Din (2017)	N.R.	N.R.	N.R.	N.R.	N.R.
Ud-Din (2017)	High-frequency	50	N.R.	N.R.	N.R.
Ud-Din (2018)	High-frequency	N.R.	N.R.	Fibrosis[†]	N.R.
Zuccaro (2021)	N.R.	N.R.	N.R.	N.R.	N.R.
Zuccaro (2019)	B-mode	N.R.	N.R.	N.R.	N.R.
Zuccaro (2021)	B-mode	6-18	Combined epidermal & dermal	N.R.	Scar outlined & photographed

Legend: B-mode: brightness-mode ultrasound (< 20 MHz); High-frequency: high-frequency B-mode ultrasound (> 20 MHz); N.R.: Not reported

Footnotes: [†]Indirect reference made in record (e.g. in introduction or discussion); [‡]Photographs taken of the scar but not specified whether used for relocation; [§]Not stated in methods, so images provided in record used by authors of this review to provide subjective judgement

The type of scar and skin thickness measurement (i.e., thickness of the dermis, epidermis, or combined epidermal and dermal measurement) was reported in 39 records (33%) (Table 3). Where reported, combined measurement of epidermal and dermal thickness was the most common method (n = 28; 24%).[21 25 31 32 35 37 58 63 65 69 70 75 76 78 82 86 87 91 94 103 108 112 125 126 128 129 145 149] Separate epidermal and dermal thickness measurements were reported in seven records (6%).[34 74 89 95 98 132 153 154] Of these records, two authors provided a rationale for this decision: each skin layer provided different information on the scar; [34] or responded differently to treatment. [74 92]

Four records (3%) directly reported that fibrosis was the scar characteristic targeted by the measurement. [36 42 96 160] One of these records also quantified hair follicle density to assess the difference between scared and unscarred skin. [42] An additional 26 records (22%) made indirect reference (i.e., within the introduction or discussion) to the measurement of fibrosis. [21 61 63 67-70 73 81-84 89 92 93 97 110 115 119 125 126 142 150 151 155 156 160] Ten records (8%) made indirect reference to the measurement of both oedema and fibrosis, [39 43 62 74 77 79 80 139 146 157] and one record made indirect reference to the measurement of oedema. [64]

Additional objective and subjective measurement methods were employed alongside ultrasound measurement in 115 records (97%) (Supplementary Table 2). All three phase 4 studies involving implementation in routine clinical practice utilised additional measurements. [99 104 109] The additional objective measurements included elastography (elasticity), cutometric assessment (pliability) and Doppler ultrasound (vascularity). The additional subjective measurements were conducted using clinician-based rating scales (e.g., Vancouver Scar Scale, used in 46 records[21 26 39 42 43 58 61 66 67 69 71 72 76 85 88 90-93 96-98 100 101 103 104 108 113-115 117 127-129 134-137 139 141-144 147 150]) or patient-reported outcome measures (PROMs). [59 63 65 75-78 85 89 91 93 96 97 100-102 105 106 108 110 112 116 118 120-124 129-131 133 135 136 139 140 142 143 155]

Methods used to relocate the scar for repeated measurements were reported in 34 records (29%) (Table 3). The most common relocation method was tracing the outline or boundaries of the scar on a transparent or translucent sheet (n = 14; 12%),[32 70 77 87 88 102 103 110 119 129 141] occasionally including prominent or bony landmarks close to the scar.[25 68 75] Photographs (n =11; 9%) and linear measurements from defined points or anatomical landmarks on or around the scar (n = 4; 3%) were also used for scar relocation. The 'worst' or 'thickest' part of the scar, as determined by patients or assessors, was chosen as the measurement site in 15 records (13%).[26 32 39 61 62 66 91 92 115 123 125 126 139 143 155]

Measurement of unscarred skin, either contralateral or adjacent to the scar, was performed in 29 records (25%). These measurements were primarily used as controls or comparators to scar measurements (n = 27, 23%).[21 31 32 36 37 42 57 60 63-65 69 76 82 85 86 89 91 92 108 110 112 127 129 130 138 152 155] Additionally, three records (3%) evaluating treatment efficacy measured both unaffected skin thickness and the thickness of a 'control' or untreated scar.[93 100 131] All instances where additional ultrasound measurements were taken of unscarred skin or untreated scars were reported as part of research initiatives aligning with phases 2 and 3 of the research-to-practice pipeline (figure 1).[51]

Reliability and measurement error

Reliability was calculated for both scarred and unscarred skin in 14 records (12%) and was generally acceptable (Supplementary Table 2). This included inter-rater reliability (n = 5; 4% of included records),[62 69 76 110 137] intra-rater reliability (n = 3; 2% of included records),[31 32 70] and both inter- and intra-rater reliability (n = 7; 6%)[21 25 91 94 123 132 141]. The intraclass correlation coefficient (ICC) was the most commonly reported reliability statistic (n = 10; 8% of included records),[21 25 69 70 76 91 94 110 132 141] where it was reported for both scar and unscarred skin measurements in four records (3%).[21 25 76 91] The reported combined thickness (i.e., epidermal and dermal) ICCs for inter-rater reliability of scarred skin ranged from 0.82 to 0.985, while the inter-rater ICC for the measurement of unscarred skin ranged from 0.33 to 0.98, with one of the four records reporting an ICC below the threshold value of 0.7 (ICC = 0.33) [25] and one record simply reported that the inter-rater ICC for scarred skin was "acceptable to high". [69] The reported intra-rater reliability for combined thickness measurements of scarred skin ranged from 0.89 to 0.983, and for unscarred skin ranged from 0.61 to 0.982, with one record reporting an ICC below the threshold of 0.7 (ICC = 0.61). [25] One record reported both the inter- and intra-rater ICCs for individual epidermal (inter-rater ICC = 0.297; intra-rater ICC = 0.809) and dermal (inter-rater ICC = 0.991; intra-rater ICC = 0.991) scar thickness measurement. [132] Four records (3% of included records) reporting reliability used Pearson's R, an undisclosed method, or description (e.g., high) as detailed in supplementary table 2. [31 62 123 137] .

Measurement error for inter-rater and intra-rater reliability of combined, epidermal or dermal thickness was reported in five records (4%) using standard error of the measurement (SEM). The inter-rater SEM for the combined epidermal and dermal thickness of scarred skin ranged from 0.11 mm to 0.5 mm, and the intra-rater SEMs ranged from 0.18 to 0.52 mm. Individual records reported SEM values for unscarred skin, and separate epidermal and dermal measurements, available in supplementary table 2. [21 25 32 94 132] Only one record reported calculation of the smallest detectable change (SDC). In that record the inter-and intra-rater SDC was calculated for both scarred and unscarred skin. The scarred skin SDCs were 1.4 mm (inter-rater) and 0.6 mm (intra-rater), and unscarred skin SDCs were 0.8 mm (inter-rater) and 0.5 mm (intra-rater). [25] The reported SEMs were all close to or below the largest SDC value reported. This finding may indicate that ultrasound can detect true variance in scar thickness above measurement error for traumatic scar and skin thickness.

Clinical, health service, implementation and feasibility outcomes:

No record specifically investigated clinical, health service, implementation or feasibility outcomes of ultrasound as a measurement-based-care initiative. Ultrasound was used to assess the clinical outcomes of scar treatment initiatives in all included records. Clinical, health service, implementation and feasibility outcomes related to ultrasound measurement were, however, reported in 67 records that focused on scar treatments.[21 25 31 32 34-36 39 42 57 58 60 62-71 73-78 82 86 90 91 93-95 99 100 102 103 109-112 115 120 123 127 129 132 133 138 139 141 145-147 150 153-160]

The clinical outcome of patient satisfaction related to ultrasound measurement was only reported in one record. Whilst patient satisfaction was not directly measured in that record, a proxy measure of satisfaction was reported by the authors stating that no paediatric patient or their caregiver refused ultrasound measurement once the purpose was explained.[25]

Timeliness was the only reported health service outcome, reported as the time required to take ultrasound measurements. Where reported, this was short, taking between one to five minutes,[25 35 112].

The most common implementation outcomes reported in the identified records were fidelity, acceptability and appropriateness. Fidelity to the measurement method was reported through the use of experienced or trained assessors (n = 7; 6%),[25 86 91 132 146 150 155] and/or utilising the same assessor/s for all measurement sessions (n = 5; 4%).[25 66 139 146 155] Differences between intended and actual measurement methods were not discussed. The training and/or experience of the assessors was discussed in 24 records (20%),[21 25 32 35 60 63 64 67-71 74 76 86 91 102 103 110 129 139 141 146 156] where measurements were either taken by a clinician (n = 13; 11%),[21 25 32 64 69-71 74 86 92 110 141 143] members of the research team (n = 6; 5%),[67 68 76 91 102 146] or by specialist sonographers and/or radiologists (n = 5; 4%).[63 103 129 139 156] Only one record reported on fidelity in the context of routine clinical practice. In this instance, ultrasound was conducted in the department of radiology, however the role or training of the staff was not reported.[109]

The acceptability and appropriateness of the ultrasound methods used in individual records were generally based on author opinion and outlined in the discussion. Acceptability was reported in 25 records (21%),[21 25 31 32 34-36 39 69 73 77 78 82 91 94 95 103 109-112 115 141 145 156 157] including for paediatric populations, where one record reported potential difficulty in measuring this population, [31] contrasting that which reported that measurement was acceptable to both children and their caregivers. [25] One record reported acceptability where the intervention being analysed by ultrasound was already part of routine clinical practice. In this instance, the authors referenced additional publications which stated that ultrasound had an accuracy of 0.5 mm, which was judged by the authors to be sufficient for assessment of scar thickness. [109 25 35 112] Potential difficulty was identified in the measurement of open wounds, [25] and traditionally hard-to-reach areas (such as the axillae or groin). [31]

The appropriateness of the ultrasound methods was reported in 46 records (39%), and was generally addressed in the discussion. [25 31 34 35 39 42 57 58 62 65 66 69-71 75-78 82 90 91 93-95 99 100 103 109 110 112 115 120 123 127 132 138 141 147 153-160] Of these records, two (2%) determined that ultrasound was not appropriate for scar measurement. The first stated that it was too inaccurate and complex; [95] and the second, which reported on initiatives within routine clinical practice, determined that the minimum resolution of the Diasonography ultrasonic scanner (Nuclear Enterprises, Edinburgh, UK) precluded its use in scars thinner than 3mm. [99]

The feasibility of ultrasound was reported in 12 records (10%).[25 31 34 73 82 91 93 109 110 133 141] Five records considered ultrasound not feasible for scar measurements. The rationale presented included high-frequency 20 MHz ultrasound having an inadequate penetration depth; [34 91] and ultrasound measurement and training of investigators requiring too much time (as reported in one record in phase 4 of the research-to-practice pipeline). [31 109 110] Another factor identified as precluding feasibility was the inability to consistently relocate the measurement site. [25] Conversely, one record reported ultrasound to be feasible in combination with Vancouver

Scar Scale (VSS) measurement, [73] and another stated that ultrasound was able to distinguish between subcutaneous fat and muscle, which was interpreted by the authors of that record to mean that skin thickness measurements were accurate. [133] The majority (n = 11; 92%) of the records reporting feasibility were research initiatives in phase 2 or 3 of the research to practice pipeline. One record examined feasibility in the context of routine clinical practice (i.e., phase 4; figure 1), [109] where it was determined that ultrasound was not suitable for use in their twelve-year longitudinal study due to changes in staff, equipment and software over such a long time period, which introduced additional variables to the measurement process that were impossible to control. [109]

Factors influencing ultrasound images and measurement methods:

The only factor that was reported to influence the imaging and measurement methods was the measurement of scars with open wounds. This was reported in one record, which determined that ultrasound and ultrasound gel was unsuitable in this instance. The authors of that record suggested the use of a flexible transparent plastic wrap, which is placed over the measurement area prior to measurement with ultrasound. [25]

Reported strengths and limitations of the measurement methods:

The safety, practicality, objectivity, versatility, reliability and non-invasive nature of ultrasound were all reported as strengths of the measurement method. [31 35-37 42 58 66 68 69 80 82 91 94 109 111 123 132 133 138 141 147 149 153 155 157 159] When compared to other subjective or clinical measurement methods (e.g., VSS) and 3D camera, ultrasound was viewed as the superior measurement method of scar and skin thickness, due to its improved accuracy, greater sensitivity to change and objectivity. [25 69 76 103 110] The ability of ultrasound to differentiate between scarred and unscarred skin was also highlighted (n = 4; 3%),[42 65 75 112] as was the versatility of ultrasound in its ability to measure a variety of anatomical areas and be used with child participants (i.e., <18 years) (n = 2; 2%).[31 156]

The poor correlation between ultrasound and histological thickness measurements, [95] and the established inverse relationship between ultrasound penetration depth and the resolution of superficial structures were identified as limitations of ultrasound in the measurement of scar thickness. [34 35 82 99 153 156 157]. One record, reporting on a longitudinal study that was conducted over twelve years, reported that the continuous development of ultrasound software and hardware over that time limited the usefulness of ultrasound. [109] Despite being reported elsewhere as acceptable (i.e., between one to five minutes[25 35 112]), one record reported that the time-consuming nature of measurement and the requirement for assessors to be trained in the operation of, and techniques required for, ultrasonography was a limitation of the method. [110] Methodologically, concerns were raised around the pressure caused by application of the ultrasound transducer to the skin, and how that may influence thickness measurement. [26 66 68 141] The size of the transducer head relative to the size of scars was also considered a potential limitation, as multiple measurements are required for quantification of larger scars. [91] Finally, it was recognised that there may be a difference between changes to the scar that can be measured by ultrasound, and what is felt and/or experienced by the patient. [78 82 125 126] It was suggested that changes that are detectable by ultrasound may be smaller than those able to be detected by patients. A minimum change in scar thickness as measured by ultrasound of between 1 to 6 mm is required before a patient may report noticing any difference to their scar thickness, [25 78] indicating that a holistic approach to scar thickness using the patient's opinion as well as objective measurement through ultrasound may be beneficial.

Guidelines or frameworks used to guide the measurement methods:

No records reported using any guidelines or frameworks to inform their measurement methods. One record utilised suggestions from The American Wound Healing Society to support the measurement of contralateral, unscarred skin thickness on the same individual as a control or comparator. [78]

Methodological Considerations:

Based on the ultrasound methods and outcomes identified in this review, a list of methodological considerations have been compiled (Supplementary Table 4). These are intended to guide the decision-making and methodological reporting of researchers and/or clinicians undertaking scar or skin thickness ultrasound measurement.

DISCUSSION:

This review mapped the methods used in the published literature to measure traumatic scar thickness using ultrasound across the research-to-practice translational pipeline. No record reported their methods with sufficient detail to allow them to be independently replicated. Overall, there was a lack of consistent rationale underpinning which skin layers (i.e., epidermis, dermis and combined) were measured, and little consideration was given to the training and experience required by assessors. The included records mainly aligned with the second and third phases of the research-to-practice pipeline (figure 1), with only three reporting the use of ultrasound in routine clinical practice. [99 104 109] This suggests a research translational gap, where ultrasound is either most commonly used as an outcome measure for research initiatives and is not regularly used to evaluate care once treatments are implemented into routine clinical practice, or that use in routine clinical practice is not reported or evaluated.

While efforts have been made to standardise ultrasound measurement procedures elsewhere in dermatology (including tumours, cancers, vascular anomalies, and systemic sclerosis[46 47]), this same effort has not yet extended to the measurement of traumatic scarring. Methodological standardisation has the potential to increase confidence in the use of ultrasound as the basis of measurement-based care initiatives for clinical decision-making, allowing patient care and scar treatments to be tailored towards individual needs. [26 161 162] Standardising the core methodological components of ultrasound measurement of scar thickness, or at the very least, creating a standardised framework for methodological decision-making, may support implementation of ultrasound measurement into routine clinical practice, supported by strategies to overcome barriers to implementation at local sites. [163]

This review identified novel insights into the identification of the composition of cutaneous scars using ultrasound, and highlighted the apparent lack of consistent understanding of, or rationale behind, what scar thickness characteristics were being measured. Fibrosis is generally understood to be the primary cause of scar thickness through the deposition of excessive extracellular matrix proteins such as collagen. [164 165] This has been confirmed through histological analysis, which has shown the presence of excess collagen and other extracellular matrix proteins in the dermis of hypertrophic scars. [40 41] An additional method for assessing the effects of scarring on the dermis, as identified by one record in this review, [42] is through quantification of the presence and density of hair follicles. This quantification may serve as a method of differentiation between scarred and physiological skin, and may also serve as a measure of skin function. [42] What is less understood, and perhaps largely overlooked, is the function of the epidermis in scar thickness. In the one record identified in this review that directly report the measurement of the epidermis, the authors noted that the measurement quantified the presence of oedema. [43] This was further supported by two records that noted that the epidermis and dermis responded differently to treatment, [74 92] indicating that there is likely a difference in the composition of the scar between these skin layers.

Cutaneous oedema has been observed using high-frequency ultrasound in other pathologies, including atopic dermatitis and skin ageing, where it is characterised by the presence of a sub-epidermal low echogenic band (SLEB), which is a hyperechoic band at the dermoepidermal junction. [166] Understanding the interplay between epidermal oedema, dermal fibrosis and the presence and density of hair follicles may result in an increased understanding of the mechanisms and treatment responses of cutaneous scarring. With better understanding, more targeted scar treatments that inform a greater understanding of scar responsivity may arise.

Another important, but potential limiting factor for the use of ultrasound to measure scar thickness raised in this review is the training and/or experience required of assessors, and the ramifications this likely has on the reliability of measurements and interpretation. [167] This review identified 24 records where assessor experience was discussed, however none made any recommendations on the optimal training and/or experience. Identifying the training requirements of assessors may prove an important step towards more widespread implementation of reliable ultrasound scar thickness measurement in research trials and as the basis for measurement-based care in routine clinical practice. [28] A panel of dermatological and ultrasound experts has previously recommended that a physician with a minimum of 300 examinations per year should hold responsibility for ultrasound measurements. [46] It has also been suggested that training existing members of clinical teams and standardising measurement method/s may be the most effective way to achieve minimum reliability standards under clinical conditions. This could allow measurement to be reliably conducted within an outpatient clinic setting by a number of healthcare providers assisting workflow, negating the requirement for patients to wait for an experienced radiographer. [25 28] In the current review reliability estimates were generally acceptable but were tested under research conditions.

Study Limitations:

Only articles available in English or with an English abstract were considered for inclusion and data extraction, which may have resulted in the omission of eligible information. Data extraction was completed on the translated English abstracts of two non-English articles, however the non-English articles themselves were not available to the authors, and thus could not be analysed. Based on the number of records included in this review, however, it is unlikely that this would have impacted review findings. An additional limitation was that authors of included records were not contacted to provide clarification or further information, as this was not feasible given the number of results identified. It should also be acknowledged that the included records were not designed to align with the specific aims of this review, which likely explains some of the lack of reporting on outcomes of interest in our review, particularly clinical, health service and implementation outcomes. Furthermore, as this review relied on published information (including grey literature), routine practices employed within organisations may not have been considered and unpublished industry sponsored reports may not have been identified.

It is also important to consider the limitations of ultrasound itself for the holistic quantification of cutaneous scarring. Ultrasound transducers are generally small, meaning that it is difficult to assess the entirety of a scar, necessitating multiple measurements. [168] Additionally, thickness is often not the only scar parameter of clinical or research interest. It has therefore been recommended that multi-modal measurement techniques are employed, which include both subjective and objective measurements. [169 170] However, use of these methods may be challenging in routine clinical practice, due to the length of time and training required. Thus, feasibility and implementation outcomes are of importance in evaluating measurement-based care initiatives involving ultrasound alone or multimodal measurement tools in scar care practice – a field in its infancy based on this review.

Future Directions:

It is intended that the results of this review will be used to inform the creation of a Delphi consensus study, leading to the formation of a guideline for the measurement of traumatic scar thickness using ultrasound. This guideline can then be used by researchers and clinicians to standardise the measurement of scars. In preparation for this study, we have provided a list of methodological considerations for assessors or practitioners when planning to conduct scar thickness measurements with ultrasound (Supplementary Table 4). Future research could also investigate aspects that were beyond the scope of this review including factors influencing the implementation of ultrasound-based care initiatives, strategies to support implementation, and how research-based initiatives could be applied in practice. Further studies are needed that compare SDCs to SEMs to interpret reliability estimates to confirm our interpretation that ultrasound may have the ability to detect true change or variance in scar thickness above measurement error, which was based on the SDC reported by a single study. Our interpretation is supported by mostly acceptable reliability estimates of ultrasound thickness for other cutaneous conditions.[29 171]

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COMPETING INTERESTS:

The authors declare no competing interests. The research presented in this publication was conducted as part of BM’s PhD, and will be included in his thesis for submission to The University of Queensland.

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AUTHOR CONTRIBUTIONS

BM and ZT conceived the project after identifying this area as a knowledge gap in existing literature. BM developed the research questions and study methodology, conducted the literature search, screened all articles and extracted data. Record screening and data extraction was completed by BM, MS, TM, and TR, with additional extraction completed by BD to assess consistency. MS, TM, TR and RK provided advice to BM on the clinical implications of ultrasound measurement. MS, RK and ZT contributed to the supervision of BM as a PhD student. BM drafted the paper, and ZT and MS provided critical appraisal of the drafted manuscript, with further advice provided by TM, TR, BD and RK.

FIGURE LEGENDS:

Figure 1: Research to clinical practice pipeline.

Figure 2. Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram for this study.

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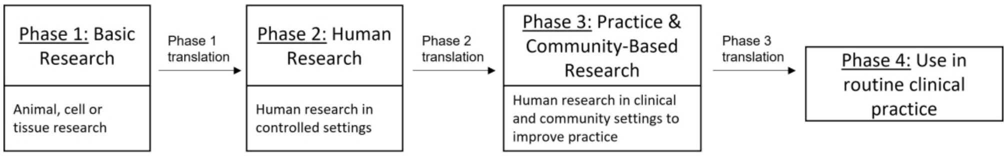

Figure 1: Research to clinical practice pipeline.

275x42mm (300 x 300 DPI)

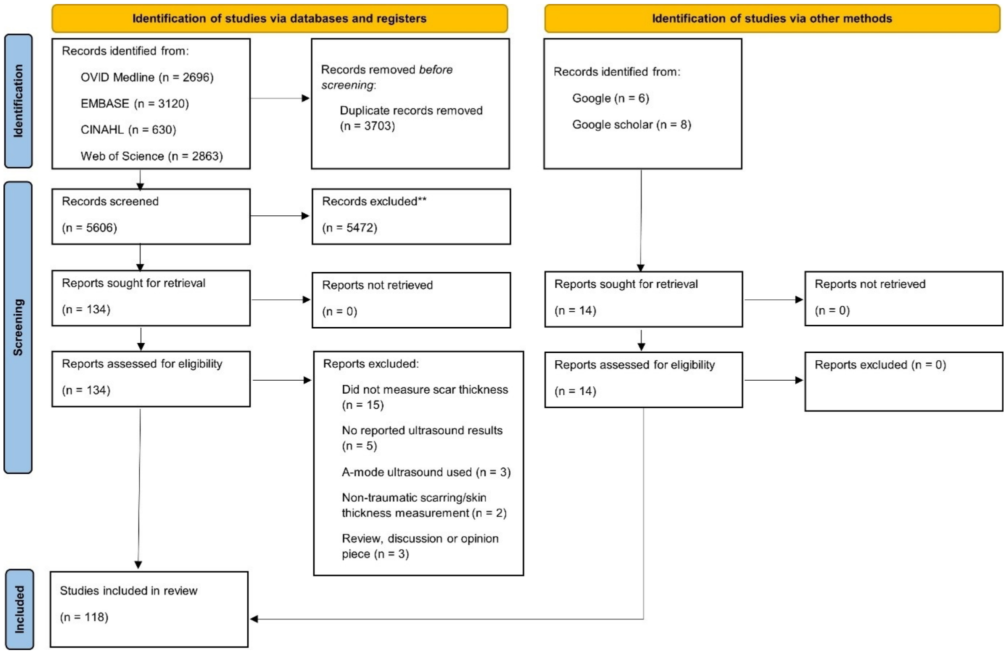

Figure 2. Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram for this study.

159x102mm (220 x 220 DPI)

Supplementary Box 1. Full search strategy for Ovid MEDLINE.

((ultrasound.ti,ab. OR ultra sound.ti,ab. OR sonograph*.ti,ab. OR ultrasonic.ti,ab. OR high-frequency.ti,ab. OR high frequency.ti,ab. OR hfus.ti,ab. OR ultrasonog*.ti,ab. OR exp Ultrasonography/)
AND

((skin.ti,ab. OR epiderm*.ti,ab. OR derm*.ti,ab. OR cutaneous.ti,ab OR scar*.ti,ab OR keloid*.ti,ab OR cicatri*.ti,ab OR exp Skin/ OR exp Dermatology/ OR exp Cicatrix/)

AND

(thickness*.ti,ab. OR thicken*.ti,ab. OR depth.ti,ab. OR volume.ti,ab. OR height.ti,ab. OR vancouver scar scale.ti,ab)

ADJ10

(measure*.ti,ab. OR quantif*.ti,ab. OR calculat*.ti,ab OR estimat*.ti,ab OR assess*.ti,ab. OR determin*.ti,ab. OR evaluat*.ti,ab OR imag*.ti,ab OR exam*.ti,ab)))

NOT (exp animals/ NOT exp humans/)

Legend: ab, abstract (searches the abstract of the publication); adj10, adjacency (search terms must be located within 10 words of one another); exp, explode (used to include all subheadings when searching MeSH headings); ti, title (searches the title of the publication)

Supplementary Table 1: Extraction categories and fields

Extraction category	Extraction field
Publication details	First author Year of publication Title of publication Country (first author) Country (study) Country (recruited) Publication type (e.g., peer-reviewed journal article, abstract) Journal name Corresponding author contact details Use of scar thickness measurement (e.g., longitudinal study, response to treatment)
Study details	Aim/objective Research questions Target population/topics Study design (e.g., RCT, mixed methods) Data and analysis (i.e., statistical methods) Removal of scar treatments before ultrasound measurement (e.g., length of time before measurement) Reason for measurement (e.g., research, clinical initiative) Inclusion/exclusion criteria Dates of data collection Ultrasound thickness collection methods (e.g., direct collection, collected from medical records) Contralateral/unaffected/comparator skin thickness measurement Other methods used Use of guidelines/frameworks for measurement methods How previously published methods/guidelines were used Research pipeline stage Setting (e.g., inpatient/outpatient clinics) Scar type (e.g., burn scar, surgical scar)
Participant details	Number of participants Population type (e.g., adult/paediatric) Gender ratio Patient involvement in thickness determination How patients were involved in thickness determination
Ultrasound methods	Ultrasound mode Device name and manufacturer Frequency used Number of measurements taken What did researchers report they were measuring (e.g., fibrosis, oedema) Anatomical locations/functional measurement units measured Patient orientation Ultrasound transducer orientation Methods used to prevent skin compression Measurement site relocation strategies Type of skin measurement (i.e., epidermis/dermis/combined) Measurer training
Psychometric properties*	Reliability Measurement error
Feasibility† outcomes	Time taken for measurement Availability of measurement method

	Ease of administration
	Number of steps required
	Number of people required to conduct measurements
	Considerations for special populations
Implementation[‡] outcomes	Acceptability
	Adoption
	Appropriateness
	Cost
	Feasibility
	Fidelity
	Sustainability
Strengths and limitations of measurement methods	Strengths
	Limitations
	Barriers
	Enablers
Findings	Ultrasound-related findings

[*] Psychometric properties as outlined in the COSMIN Risk of Bias tool to assess the quality of studies on reliability or measurement error of outcome measurement instruments[1]

[†] Feasibility outcomes as per Prinsen *et al.*[2]

[‡] Implementation outcomes as per Proctor *et al.*[3]

Supplementary Table 2. Additional measurement methods used alongside ultrasound in included studies

First author (year)	**Objective measurement methods**	**Clinician-based rating scale**	**PROM**
Journal articles			
Agabalyan (2017)	Histology	-	-
Alsharnoubi (2018)	Laser Doppler perfusion	VSS	-
Alsharnoubi (2018)	Laser Doppler perfusion	VSS	-
Alshehari (2015)	-	VSS	-
Avetikov (2018)	-	-	-
Berry (1985)	Transcutaneous oxygen measurement	Scar redness and hypertrophy rating scale (0-5 Likert scale)	Scar redness and hypertrophy rating scale (0-5 Likert scale)
Blome-Eberwein (2012)	Doppler flowmeter – vascularity Cutometer – pliability Semmes-Weinstein monofilament Aesthesiometer testing set – sensation	VSS POSAS-O	POSAS-P
Blome-Eberwein (2016)	Cutometer – pliability Dermaspectrometer – colour Semmes-Weinstein Aesthesiometer Monofilament Testing Set – sensation	VSS POSAS-O	POSAS-P
Blome-Eberwein (2019)	-	VSS	-
Cai (2019)	-	Clinical evaluation	-
Candy (2010)	Spectrocolorimeter – colour	VSS	-
Chae (2016)	Spectrophotometer – pigmentation	VSS POSAS-O	POSAS-P
Chang (2014)	-	VSS Photographic evaluation (0-10 VAS)	-
Chan (2004)	Cutometer – viscoelasticity Spectrophotometer – pigmentation	-	-
Cheng (2001)	-	VSS	-
Cho (2014)	Mexameter – colour	Treatment efficacy (0-10 VAS)	Itching scale (0-4 Likert scale)

	Tewameter – trans-epidermal water loss Sebumeter – sebum Cutometer – elasticity		
Danin (2012)	Cutometer – elasticity	VSS	-
Deng (2019)	DermaLab Combo – colour Dermoscopy – vascularity	POSAS-O	-
Deng (2021)	-	VSS	-
Deng (2021)	Doppler – blood perfusion Dermlite Foto IIPro – erythema	POSAS-O	POSAS-P
Dunkin (2007)	-	-	-
Elrefaie (2020)	Ultrasound – echogenicity, compressibility & vascularity	VSS	-
Engrav (2010)	Durometer – hardness Chromameter – colour	Clinical appearance based on photographs	-
Fabbrocini (2016)	-	mVSS (vascularity, pigmentation, pliability)	-
Fong (1997)	Cutometer – elasticity	Clinical rating – colour change, consistent itch, hypersensitivity, blistering	-
Fraccalvieri (2013)	Colour power Doppler – vascularisation	VSS Visual analogue scale – pain and itch	
Fraccalvieri (2011)	Histology Echocontrastography – neovascularisation	-	-
Gankande (2014)	DermLab combo – erythema & elasticity	mVSS (some participants)	-
Ge (2022)	-	POSAS-O Subjective reports on patient range of movement	POSAS-P
Gee Kee (2016)	3D photography – thickness	POSAS-O	POSAS-P
Guo (2020)	Ultrasound – blood flow grade Shear wave elastography – scar stiffness	-	-

Huang (2017)	-	-	-
Huang (2021)	-	-	-
Huang (2020)	Shear wave elastography – scar stiffness	-	-
Issler-Fisher (2021)	-	VSS POSAS-O	POSAS-P
Issler-Fisher (2020)	-	VSS POSAS-O	POSAS-P Patient pain & itch scales
Issler-Fisher (2017)	-	VSS POSAS-O	POSAS-P Patient pain, itch & quality of life rating scales
Joo (2020)	-	VSS	Pain severity (0-10 VAS)
Katz (1985)	Cicatrometer – firmness	-	-
Kemp Bohan (2021)	-	-	-
Kim (2018)	-	-	-
Lacarrubba (2008)	-	Clinical evaluation of lesion size	-
Lau (2005)	-	VSS	-
Lee (2020)	-	mVSS (height, pliability, vascularity, pigmentation) POSAS-O	POSAS-P
Lee (2019)	-	mVSS (height, pliability, vascularity, pigmentation) POSAS-O	POSAS-P
Li (2013)	Micrometer – tissue thickness Force/torque sensor – load applied to scar	-	-
Li (2020)	Cutometer – elasticity Mexameter – colour PeriCam PSI system and mexameter – blood supply	VSS	Quality of life questionnaire
Li (2021)	Laser Doppler flowmetry – perfusion	VSS	-
Li (2018)	Spectrocolourimeter – scar colour	VSS	Pain & itch (0-10 VAS)
Li (2021)	-	VSS	Treatment satisfaction
Li-Tsang (2005)	Spectrocolourimeter – scar colour	VSS	Pain & itch (VAS scale not specified)
Li-Tsang (2006)	Spectrocolorimeter – colour	VSS	Pain & itch (VAS)

Li-Tsang (2010)	Spectrocolorimeter – colour	VSS (pliability)	Pain & itch (10-point VAS)
Lobos (2017)	-	Modified Seattle Scar Scale Clinical opinion	-
Mamdouh (2021)	-	VSS	Patient satisfaction (VAS)
Meirte (2016)	-	-	-
Miletta (2021)	Colourmeter – scar colour Dermal torque meter – scar compliance	Unclear, likely POSAS-O	Unclear, likely POSAS-P Short Form 36 Quality of Life Survey
Nedelec (2014)	Cutometer – elasticity Mexameter – colour	-	-
Nedelec (2008)	Cutometer – elasticity Mexameter – colour	mVSS	-
Nedelec (2019)	Cutometer – elasticity Mexameter – colour	-	-
Nedelec (2020)	Cutometer – elasticity Mexameter – colour	-	Pain & itch (10cm line VAS)
Nicoletti (2015)	-	-	-
Niessen (1998)	Histology	-	-
Reinholz (2020)	3D topographic imaging device	POSAS-O	Dermatology Quality of Life Index POSAS-P
Reinholz (2016)	Optical coherence tomography – thickness	POSAS-O	Dermatology Quality of Life Index POSAS-P
Schwaiger (2018)	3D topographic imaging device	-	-
Simons (2017)	3D camera – scar height	POSAS-O	-
Soykan (2014)	Slide calliper – dimensions	POSAS-O	POSAS-P
Timar-Banu (2001)	Metric ruler – dimensions	Validated 3-point scoring system for redness, hardness, itching & pain	-
Ud-Din (2019)	Optical coherence tomography – thickness Histology	-	-
van den Kerckhove (2005)	Chromameter – erythema	-	-
van der Veer (2010)	Slide calliper – dimensions	-	-
Wang (2009)	Histology	-	-
Wang (2010)	-	-	-

Wiseman (2020, 2021)	-	POSAS-O	POSAS-P Numeric rating scale for itch Toronto Paediatric Itch Scale CH-9D BBSIP
Wood (1996)	-	VSS	-
Xuan (2021)	Histology	-	-
Yeol Lee (2022)	Cutometer – elasticity Elastography	mVSS	-
Yim (2010)	Cutometer – elasticity Tewameter – trans-epidermal water loss Mexameter – colour	-	-
Zadkowski (2016)	-	VSS	-
Abstracts			
Agabalyan (2016)	Histology	-	-
Bajouri (2018)	-	VSS	-
Bezugly (2019)	Clinical or histopathological diagnosis	-	-
Bezugly (2014)	-	-	-
Blome-Eberwein (2011, 2012)	Doppler vascularity, elasticity and sensation	VSS	Pain and itching scale (0-10 Likert scale)
Blome-Eberwein (2012)	-	-	-
Blome-Eberwein (2014)	Doppler flowmeter – vascularity Cutometer – pliability Semmes-Weinstein monofilament aesthesiometer testing set – sensation	VSS	POSAS-P
Cho (2012)	-	VSS	-
Cho (2012)	CK-MPA Multi-Probe adaptor – pigmentation, erythema and trans-epidermal water loss Cutometer – elasticity	-	-
Comstock (2018)	Computer-based tools – Thickness & pliability	Unclear, likely POSAS-O	Unclear, likely POSAS-P

Cooper (2021)	Colorimeter – pigmentation	Unclear, likely POSAS-O	Unclear, likely POSAS-P
Du (2006)	-	-	-
Edgar-Lacoursière (2022)	Cutometer – elasticity Mexameter – colour	-	-
El-Zawhary (2007)	Histology	-	-
George (2019)	-	-	-
Jacobs (2016)	Cutometer – pliability Colorimeter – colour	POSAS-O	-
Jang (2009)	Mexameter – pigmentation Tewameter – trans-epidermal water loss Sebumeter – sebum Cutometer – elasticity Laser Doppler – perfusion	-	-
Kim (2009)	Histology	VSS	-
Li (2016)	Spectrocolourimeter – scar colour	VSS	Patient report of pain & itch
Li-Tsang (2011)	-	VSS (thickness, pliability and pigmentation)	-
Li-Tsang (2010)	Histology Spectrocolourimeter – scar colour	VSS	Self-report questionnaire
Maari (2017)	Cutometer – elasticity Mexameter – pigmentation	-	-
Moortgat (2020)	Cutometer – elasticity Chromameter – colour Tewameter – trans-epidermal water loss Corneometer – hydration	Unclear, likely POSAS-O	Unclear, likely POSAS-P
Nedelec (2018)	Cutometer – elasticity Mexameter – colour	-	-
Peters (2018)	Cutometer – elasticity Colourimeter – colour	POSAS-O	POSAS-P
Seo 2011	Cutometer – elasticity		
Siwy (2016)	Colourimeter – colour Torque meter – pliability & elasticity	-	SF-36 Quality of Life Measurement POSAS-P
Timina (2013)	-	-	-

Tu (2014)	-	VSS	-
Ud-Din (2017)	Laser perfusion imaging Optical coherence tomography – thickness Histology	-	-
Ud-Din (2017)	Optical coherence tomography – thickness	-	-
Ud-Din (2018)	Optical coherence tomography – thickness Histology	-	-
Zuccaro (2021)	Multi-parameter skin analysis device	VSS Unclear, likely POSAS-O	Unclear, likely POSAS-P
Zuccaro (2019)	Acoustic radiation force impulse ultrasound elastography	-	-
Zuccaro (2021)	Acoustic radiation force impulse – stiffness DermLab Combo elasticity probe – elasticity DermLab Combo colour probe – colour	VSS POSAS-O (did not include surface area and relief subscales)	POSAS-P

Legend: (m)VSS: (Modified) Vancouver Scar Scale; POSAS: Patient and Observer Scar Assessment Scale (POSAS-O: POSAS observer scale; POSAS-P: POSAS patient scale); VAS: Visual Analogue Scale; CHU-9D: Child Health Utility-9D; BBSIP: Brisbane Burn Scar Impact Profile

Supplementary Table 3: Reliability of ultrasound methods reported in each included study

First Author (year)	**Reliability Test & Measurement Error**	**Reliability & Measurement Error Test Statistics & Details**
Inter-rater reliability		
Anthonissen (2015)	ICC; SEM	Epidermal – 0.297; 0.02mm Dermal – 0.991; 0.13mm
Chang (2014)	Pearson correlation	R=0.90, p<0.001
Dunkin (2007)	N.R.	N.R.
Fong (1997)	ICC	0.93, p=0.146
Gankande (2014)	ICC (95% CI)	Individual site: **Rater 1 vs rater 2** 'Best scar' – 0.95 (0.92, 0.96) 'Worst scar' – 0.95 (0.91, 0.97) 'Normal skin' – 0.94 (0.91, 0.96) **Rater 1 vs rater 3:** 'Best scar' – 0.86 (0.78, 0.91) 'Worst scar' – 0.91 (0.85, 0.95) 'Normal skin' – 0.92 (0.88, 0.95) **Rater 2 vs rater 3:** 'Best scar' – 0.93 (0.89, 0.95) 'Worst scar' – 0.96 (0.92, 0.97) 'Normal skin' – 0.95 (0.92, 0.97) Average site: **Rater 1 vs rater 2** 'Best scar' – 0.97 (0.94, 0.99) 'Worst scar' – 0.98 (0.96, 0.99) 'Normal skin' – 0.97 (0.93, 0.98) **Rater 1 vs rater 3** 'Best scar' – 0.90 (0.77, 0.95) 'Worst scar' – 0.97 (0.91, 0.98) 'Normal skin' – 0.96 (0.92, 0.98) **Rater 2 vs rater 2** 'Best scar' – 0.95 (0.88, 0.98) 'Worst scar' – 0.98 (0.94, 0.99) 'Normal skin' – 0.98 (0.97, 0.99)
Lau (2005)	ICC	0.84, p<0.01
Lee (2020)	ICC	"Acceptable to high"
Lee (2019)	ICC (95% CI); SEM	Scar: Single: 0.957 (0.934-0.973) Average: 0.985 (0.977-0.991) SEM: 0.10 mm Unscarred skin: Single: 0.967 (0.949-0.980) Average: 0.989 (0.982-0.993) SEM: 0.04 mm
Nedelec (2008)	ICC (95% CI)	Most severe scar: 0.90 (0.84-0.95) Less severe scar: 0.91 (0.85-0.95) Donor site: 0.89 (0.82-0.94) Normal skin: 0.85 (0.75-0.92)
Seo (2011)	N.R.	"High"
Simons (2017)	ICC (95% CI); SEM	Scar: 0.82 (0.7-0.89); 0.05 cm Normal skin: 0.33 (0.08-0.54); 0.03 cm
Van Den Kerckhove (2003)	ICC (95% CI); SEM	One day: 0.88 (0.81-0.95); 0.29 mm

		Day-to-day: 0.94 (0.90-0.98); 0.21mm
Intra-rater reliability		
Anthonissen (2015)	ICC; SEM	Epidermal – 0.809; 0.01mm Dermal – 0.991; 0.13mm
Gankande (2014)	ICC (95% CI)	'Best scar' – 0.97 (0.89, 0.94) 'Worst scar' – 0.92 (0.88, 0.95) 'Normal skin' – 0.86 (0.81, 0.89)
Gee Kee (2016)	N.R.	N.R.
Lau (2005)	ICC	Intra-rater: 0.98, $p<0.01$
Lee (2019)	ICC (95% CI)	Scar: Single: 0.951 (0.871-0.987) Average: 0.983 (0.953-0.966) SEM: 0.10 mm Unscarred skin: Single: 0.948 (0.881-0.976) Average: 0.982 (0.954-0.993) SEM: 0.04 mm
Li (2013)	ICC	0.89
Seo (2011)	N.R.	"High"
Simons (2017)	ICC (95% CI); SEM	Scar: 0.95 (0.91-0.97); 0.02 cm Normal skin: 0.61 (0.41-0.75); 0.02 cm
Van Den Kerckhove (2003)	ICC (95% CI); SEM	0.98 (0.97-0.99); 0.11mm
Wang (2010)	SE	Peak: 0.032 3 months: 0.018 6 months: 0.399 9 months: 0.353

Abbreviations used in tables: N.R.: Not reported; ICC: Intraclass Correlation Coefficient; 95% CI: 95% Confidence Interval; SEM: Standard Error of Measurement; SE: Standard Error

Summary of findings for measurement error:

The reported inter-rater SEM measurements for the combined (i.e., epidermal and dermal) thickness measurement of scars was reported in two records as 0.11 mm[4] and 0.5 mm.[5] The inter-rater SEM for the combined thickness measurement of unscarred skin was also calculated in one record (SEM = 0.3 mm).[5] The inter-rater SEM was calculated in one record for the measurement of epidermal (SEM = 0.02 mm) and dermal (0.13) measurements[6], and one record reported only the dermal SEM for scar thickness (SEM = 0.1 mm) and unscarred skin (0.04 mm).[7] The intra-rater SEM for the combined thickness measurement of scarred skin ranged from 0.18 mm to 0.52 mm, and was measured at 0.2 mm for unscarred skin in one record.[5] One record reported the intra-rater SEM for epidermal (0.01 mm) and dermal (0.12 mm),[6] and one record reported the intra-rater SEM for dermal scar (0.1 mm) and unscarred skin (0.04).[7]

Supplementary Table 4. Methodological considerations for researchers and/or clinicians undertaking measurement of scar thickness using ultrasound.

Consideration	Details & examples of considerations	Publications in our review addressing the consideration	Details reported in included review records
Preventing skin compression during measurement	Using standoff methods (e.g., ultrasound gel, water bath) to prevent transducer touching the skin	5,8-12	- Use of ultrasound gel to prevent contact between ultrasound transducer and skin surface to minimise compression applied by direct application of transducer [5,8-11] - Silicone pad placed underneath transducer [12]
	Application of minimal pressure by transducer	13-17	- Transducer held to maintain minimal pressure on scar [13,14,16] - Training users to apply minimal force on transducer to prevent scar or skin distortion [15,17]
	Deliberately compressing skin to quantify scar compressibility	18-20	- Measurement of thickness with and without compression with transducer [18,20] - Thickness measurements taken using TUPS, which uses controlled and metered compression during measurement [19]
Orienting the patient	Orienting the patient during measurement (e.g., upright, supine, prone or seated)	7,17,21	- Patient supine throughout measurement to allow measurement to be taken in the same position [7,17,21]
	Maintaining patient stillness during measurement	8	- Patients asked to hold breath during measurement of scars on the chest to allow shear-wave ultrasound [8]
Placing ultrasound transducer	Orientating ultrasound transducer [e.g., vertical (superior to inferior/cranial to caudal), horizonal (medial to lateral)]	22	- Direction of transducer recorded to ensure consistency [22]

	Orienting the transducer in relation to the scar (e.g., perpendicular)	8,14,16,17,21,23-25	- Transducer oriented perpendicular to the skin surface to provide optimal image [8,14,17,21,23-25]
	Measuring difficult/tight areas (e.g., axillae or other joints)	5	- Exclusion of fingers and toes in paediatric measurements due to size of measurement area and thin skin [5]
Relocating scars for longitudinal measurement	Mapping measurement area (e.g., tracing, schematic diagram)	5,11,15,17,19,21,26-31	- Scars traced using translucent paper [17,19,21,26,28,30,31] - Scars and surrounding anatomical landmarks traced using translucent paper [15] - Scar mapped on transparent paper, which was then cut out [27] - Scar mapped with drawing, no elaboration provided [29] - Scars traced using Visitrak (Smith & Nephew Medical Limited, England) [5,11]
	Photographing measurement area	23,25,32	- Assessed area marked and photograph taken in initial consultation [23,32] - Photographs of scars taken [25]
	Measuring specific scar locations (e.g., centre of scar, worst area of scar, counting transducer lengths)	5,7,8,12,18-20,22,29,32-36	- Measurement taken at standardised transducer lengths along surgically created scars of pre-specified dimensions [33] - Measurements taken at thickest/most severe point [18-20,29,32,34,36], as determined by the patient and/or clinician [7] - Transducer placed on thickest site on peripheral regions [8] - Transducer placed on area initially identified to have greatest burn depth [22]

			- Measurement area selected by the measurer with -selected area marked with tape [12] - Measurements taken at set linear distances from cranial/caudal border of linear sternal scar [35]
	Conducting linear measurements from nearby anatomical landmarks	[16,37]	- Linear measurements from anatomical landmark to measurement site [16] - Transducer placement mapped in 3-dimensional space using a surgical precision tracking arm [37]
Acclimatising scar to measurement conditions	Removing scar treatments prior to ultrasound measurement	[7,11,19,21,23-25,27,28,38,39]	- Pressure garments removed 10 minutes before measurement [27] - Pressure garments removed 15 minutes before measurement to regain original (uncompressed) scar thickness or to reduce blanching effects on measurement [19,39] - Pressure garments/gels/moisturisers removed 20 minutes before measurement [7,21,28] - Pressure garments removed 30 minutes before measurement [11,24,25,38] - Sequential measurement of scars following direct treatment with vacuum massage at 5, 30, 60 and 120 minutes to monitor effect of treatment [23]
	Acclimatising patient to room prior to measurement	[4,17,21,28,40-45]	- Patients rested for minimum 5 minutes before measurement [4,17,21] - Scar exposed to room conditions for 10 minutes [28] to allow equilibrium to be reached with surrounding environment [40] - Patients resting in room with constant temperature for 15 mins [41] to allow scar to stabilise [43]

			- Patients rested for 20 minutes prior to measurement [28,44] - Patients resting for 10 minutes before repeated measurements taken [42] - Patients wait in testing room holding position for 5 min before measurement to stabilise cutaneous blood flow [4] - Patients allowed to adapt in controlled room to exclude external variables [45]
	Maintaining patient position before measurement	[10,12]	- Patients remained supine for at least 5 minutes before measurement to avoid artefacts on Doppler imaging [12] - Patients allowed to acclimatise to room and assumed a supine position for a minimum of 10 minutes before measurements of biophysical parameters [10]
Measuring different skin layers	Measuring epidermis and/or dermis individually	[6,23,36,44,46-53]	- Measurement of epidermal, dermal and combined epidermal and dermal thickness to allow comparison with histological measurement [46,47] - Measurement of the epidermal and dermal thickness [44,48], combined with layer acoustic density [6] - Measurement of the epidermal, dermal and subcutaneous thickness, combined with acoustic density [49,50] - Measurement of dermal thickness as treatment thought to affect/target the dermis [23,36,51-53]
	Measuring both epidermis/dermis combined (no	[4,5,7,10,11,14,16,17,21,22,25,27,34,39,54-67]	- Combined epidermal and dermal thickness measurement to provide information on the full thickness of the scar [4,5,7,10,11,14,16,17,21,22,25,27,34,39,54-67]

	individual measurement)		
Measurement objective	Measuring fibrosis/oedema/hair follicles	7,9,10,12,13,15,16,23,24,28-31,33,35,36,44,53,57,59,60,62,63,68-81	- Measurement of fibrosis or collagen architecture [7,10,16,23,28-31,33,35,36,44,53,57,60,62,63,68,69,71-73,76-78,81] - Measurement of inflammation/oedema [13] - Quantification of the sub epidermal low echogenic band, indicating oedema [59] - Measurement of both fibrosis and oedema [9,12,15,24,57,70,74,75,79,80] - Measurement of the presence and density of hair follicles to differentiate scarred and unscarred skin[53]
Factors influencing scar site measurement	Measuring contralateral skin/control scar	8,13,14,22,28,29,51,54-57,82-87 5,7,11,17,21,24,37,42,53,58-60,65,88,89 38,39,44,78,80,81	- Measurement of additional, non-scarred subjects [54,78] - Measurement of unscarred/unaffected skin on same subject as scar measurement contralaterally or at anatomically similar location to provide normative measurements for skin thickness [5,7,8,11,13,14,17,21,22,28,29,37-39,42,44,51,53,55-60,65,80,84-89] - Measurement of both untreated scar and unaffected skin [81-83] - Measurement of a control scar subjected to care as usual treatment on the same individual [24]
	Measuring open wounds or sores in the scar	5	- Use of flexible transparent plastic wrap placed over the measurement area to prevent contact between ultrasound gel and transducer with the open wound/sore [5]
	Operator training and/or experience	5,7,11,13,15,17,19,23,26-28,30,38,39,57,60,65,71,72,86,90-92	- Trained outcome assessor [5,12,15,17,26,71] - Measurements taken by radiologist/sonographer [27,65,72,91]

		- Assessors with burn experience [86,92] - Ultrasound located in department of radiology [90] - Measurements conducted by trained therapist/doctor under guidance of experienced radiologist [11,13,28,38] - Measurements conducted by trained clinicians who use device regularly and received training by company representative of devices [7,60] - Device-specific training provided: 1 week [19]; 3 sessions of 3 hours for 3 weeks, plus 10 independent assessments of scars using study protocol [39]; training provided over 3 months [30]; physical therapist trained in ultrasound application [23]
Number of measurements per scar	4,5,7,8,10,11,19,22,24,25,30,33,36,39,43,44,46,51,53,56,59,60,65,67,78,84,91,93	- 3 ultrasound images taken from each patient [8,10,25,30,36,43,44,46,51,53,56,59,78,84] - Clearest of 3 measurements used [11] - 3 measurements in 3 locations across scar used. Individual and average measurements reported [39] - Measurements performed in duplicate [33,93] - Measurements taken at different points of the scar, thickest used for analysis [91] - 5 measurements of each site [5,22] - 9 measurements taken, removal of maximum and minimum, 7 measurements used for average [19] - Measurements taken by 3 assessors at 3 different time points during day [7,60] - Measurement of 2 sites on the same scar [24] - Single ultrasound image taken for analysis [67]

Use of additional measurement tools as well as ultrasound measurements	Using additional objective assessment instruments (e.g., histology, colour Doppler ultrasound, cutometer, colourimeter)	5,8-10,12,14,16,17,20-22,24-26,28,30,31,34,35,39-47,49,52,55-58,65,67-69,74-79,81-83,85-91,94-110	- Histology/immunohistochemistry [12,16,46,47,49,57,77,78,87,99,102,107,109] - Blood flow and blood perfusion measurement using laser Doppler perfusion imaging, flowmetry or PeriCam, and scar colour and micro-vessel percentage using dermoscopyolour and micro-vessel percentage. [34,68,69,82,83,85,86,91,98,100,107] - Oximeter [40] - Infra-red camera [40] - Measurement of scar stiffness or pliability/elasticity using elastography or cutometer [8,14,17,20,21,24-26,28,42,45,52,56,65,81-83,85,88,89,95,97,98,100,103-105] - Measurement of sensation using Semmes-Weinstein filaments [81-83,85] - Measurement of scar colour (including pigmentation and erythema) using spectrophotometer, colourimeter, chromameter, mexameter or Dermlite Foto IIPro [17,21,24-26,31,41,43-45,52,55,65,67,79,81,86,89,90,95-98,100-106,110] - Measurement of trans-epidermal water loss using Tewameter or scar hydration using Corneometer [45,52,95,98] - Measurement of sebum level using sebumeter [95,98] - Measurement of hardness using durometer [90] - Measurement of neovascularisation using echocontrastography [57] - Measurement of scar dimensions (e.g., scar height and volume) using 3D camera, 3D imaging methods, ruler or calliper [5,9,10,22,35,74,76]

		- Measurement of skin thickness using micrometer or optical coherence tomography [16,30,58,75,107-109] - Measurement of scar firmness or deformation using cicatrometer, force/torque sensor (in line with ultrasound to measure load applied) or torque meter [30,31,106] - Multi-parameter skin analysis device [65] - Measurement of erythema and elasticity using probes of DermaLab Combo [39] - Multi-probe adaptor taking multiple measurements (pigmentation, erythema, trans-epidermal water loss) [95]
Using subjective assessment instruments (e.g., clinical rating scales, PROMs)	18,19,22,27-29,32,36,39,40,43,44,48,51,55,56,60,65,66,68-71,79-83,85,86,90,91,93-97,99,110-114	PROMs: - Measurement of scar quality using POSAS patient report [7,22,29,32,44,55,60,62,63,65,74-76,81,85,94,96,105,106,113,114] - Subjective rating scales for scar symptoms (e.g., pain, itch) or subjective scar severity ratings [25,29,40,41,52,62,63,71,79,82,83,92,101,102,110,114] - Patient quality of life questionnaires [74,75,100,106] - Measurement of generic health-related quality of life using CHU-9D [62,63] - Measurement of scar-specific health-related quality of life using BBSIP [62,63] - subjective evaluation of response to treatment/treatment satisfaction [80,115] Clinical rating scales: - Measurement of scar quality using POSAS observer report [7,22,29,32,44,52,55,60,62,63,65,74-76,81,85,86,96,97,105,113-115]

			- Measurement of physical scar characteristics using VSS or modified versions of the VSS [7,17-19,27,29,32,34,36,37,39,41-43,48,55,56,60,64,65,68-71,79-85,91-94,99-102,110-112,114,116,117] - Measurement of scar characteristics in relation to unscarred skin using Seattle Scar Scale or modified Seattle Scar Scale [72] - Subjective rating scales for scar symptoms (e.g., pain, itch) as assessed by the clinician and/or researcher and/or clinical evaluation of scar severity [10,28,40,51,56,66,72,90,91,93,95]
	Determining the order of measurement	5	**-** Standardised order of measurement: 3D photograph, POSAS-O, then ultrasound [5] - Order of device use not specified [34,68,69,82,83,85,86,91,98,100,107]

Abbreviations: TUPS: Tissue Ultrasound Palpation System; 3D: three-dimensional; POSAS: Patient and Observer Scar Assessment Scale; CHU-9D: Child Health Utility 9D; BBSIP: Brisbane Burn Scar Impact Profile; VSS: Vancouver Scar Scale; mVSS: Modified Vancouver Scar Scale; POSAS-O: Patient and Observer Scar Assessment Scale, observer measure

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Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	3-4
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	5-7
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	7
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	7
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	8-10
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	8
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	9
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	9
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	10-11
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	10-11 and supplementary table 1
Critical appraisal of individual	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe	N/A

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
sources of evidence§		the methods used and how this information was used in any data synthesis (if appropriate).	
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	10-11
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	11-12
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	12-15
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Results section (11-46)
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Results section (11-46)
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	47-49
Limitations	20	Discuss the limitations of the scoping review process.	49-50
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	50-51
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	51

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

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Ultrasound measurement of traumatic scar and skin thickness: A scoping review of evidence across the translational pipeline of research-to-practice

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Ultrasound measurement of traumatic scar and skin thickness: A scoping review of evidence across the translational pipeline of research-to-practice*

Running Title: Review of scar thickness measurement with ultrasound

Brandon Meikle[1,2**], Megan Simons[2,3,7], Tamsin Mahoney[4], Tristan Reddan[5,6], Bryan Dai[2], Roy M Kimble[1,2,6,7] and Zephanie Tyack[2,8]

[1] Centre for Children's Burns and Trauma Research, Queensland Children's Hospital, Brisbane, Queensland, Australia

[2] Children's Health Research Centre, Faculty of Medicine, The University of Queensland, Herston, Queensland, Australia

[3] Occupational Therapy Department, Queensland Children's Hospital, Children's Health Queensland Hospital and Health Service, Brisbane, Queensland, Australia

[4] Surgical, Treatment and Rehabilitation Services (STARS), Metro North Hospital and Health Service, Brisbane, Queensland, Australia

[5] Medical Imaging and Nuclear Medicine, Queensland Children's Hospital and Health Service, Brisbane, Queensland, Australia

[6] School of Clinical Sciences, Faculty of Health, Queensland University of Technology, Brisbane, Queensland, Australia

[7] Pegg Leditschke Children's Burns Centre, Queensland Children's Hospital, Children's Health Queensland Hospital and Health Service, Brisbane, Queensland, Australia

[8] Australian Centre for Health Service Innovation (AusHI), Centre for Healthcare Transformation, and School of Public Health and Social Work, Queensland University of Technology, Brisbane, Queensland, Australia

** Corresponding author

E-mail: brandon.meikle@uq.net.au (BM)

*Parts of this paper were presented at the Australian and New Zealand Burn Association (ANZBA) 2022 Annual Scientific Meeting, the 2022 Centre for Children's Health Research Symposium, Child Health Research Centre, The University of Queensland, and the 2023 British Burn Association Annual Conference.

ABSTRACT:

Objectives: To identify the ultrasound methods used in the literature to measure traumatic scar thickness, and map gaps in the translation of these methods using evidence across the research-to-practice pipeline.

Design: Scoping review

Data Sources: Electronic database searches of Ovid MEDLINE, Embase, Cumulative Index of Nursing and Allied Health Literature (CINAHL) and Web of Science. Grey literature searches were conducted in Google. Searches were conducted from inception (date last searched 27/05/2022).

Data Extraction: Records using B-mode ultrasound to measure scar and skin thickness across the research-to-practice pipeline of evidence were included. Data was extracted from included records pertaining to: methods used; reliability and measurement error; clinical, health service, implementation and feasibility outcomes; factors influencing measurement methods; strengths and limitations; and use of measurement guidelines and/or frameworks.

Results: Of the 9309 records identified, 118 were analysed (n = 82 articles, n = 36 abstracts) encompassing 5213 participants. Reporting of methods used was poor. B-mode, including high-frequency (i.e., > 20 MHz) ultrasound was the most common type of ultrasound used (n = 72 records; 61% of records), and measurement of the combined epidermal and dermal thickness (n = 28; 24%) was more commonly measured than the epidermis or dermis alone (n = 7, 6%). Reliability of ultrasound measurement was poorly reported (n=14; 12%). The scar characteristics most commonly reported to be measured were epidermal oedema, dermal fibrosis and hair follicle density. Most records analysed (n = 115; 97%) pertained to the early stages of the research-to-practice pipeline, as part of research initiatives.

Conclusions: The lack of evaluation of measurement initiatives in routine clinical practice was identified as an evidence gap. Diverse methods used in the literature identified the need for greater standardisation of ultrasound thickness measurements. Findings have been used to develop nine methodological considerations for practitioners to guide methods and reporting.

STRENGTHS AND LIMITATIONS OF THIS STUDY:

- Use of the Australian Government Department of Health and Aged Care Medical Research Future Fund research-to-practice pipeline phases to categorise records allowed identification of gaps in the use of ultrasound for clinical practice.
- Clinical, health service, implementation and feasibility outcomes related to ultrasound measurement in included records were summarised to determine what is needed to close the research-to-practice gap for ultrasound measurement of scar thickness.
- A limitation is that only articles available in English or with an English abstract were considered for inclusion and data extraction, thus findings are likely most relevant to English speaking countries.

INTRODUCTION:

Traumatic cutaneous injury, caused by sharp object penetration (e.g., surgery or vaccination) or burns (including thermal, chemical and friction) may result in the formation of hypertrophic scarring. (1) Hypertrophic scars result from an aberrant cutaneous healing response that leads to the formation of red, raised scars, often accompanied by pruritus and skin tightening, which remain within the boundaries of the initial injury. (2-7) The sequelae of hypertrophic scars can impact on patient's physical and psychosocial quality of life. (8, 9)

A characteristic of hypertrophic scarring that both patients and clinicians have identified as being important, and which has subsequently been used as a way to measure clinical and treatment outcomes, is scar thickness. (9-17) Scar thickness can be measured both subjectively, through clinician assessment and patient-reported outcomes, or objectively, utilising medical imaging methods. (18, 19) The pathological complexity of hypertrophic scars means that they generally extend below the level of the surrounding skin, supporting the use of medical imaging modalities such as ultrasound for thickness quantification, as these are capable of providing information about subcutaneous structures and processes. (19, 20) Scar thickness measurement using ultrasound can be conducted in both clinical and research contexts. Where routine measurements like ultrasound are used to guide clinical decision-making and treatment, this practice is known as measurement-based care. (21)

Ultrasound is a safe, non-invasive and largely cost-effective (compared to other imaging modalities) imaging method with measurement utility in both adult and paediatric populations. (22-24) Modern B-mode (brightness mode) ultrasound, particularly high- (i.e., ≥20 MHz) or ultra-high frequency (30-100 MHz) (25) ultrasonography, allows differentiation between the epidermis and dermis, which permits quantification of skin layer-specific scar characteristics. This differentiation may allow assessors to observe and understand the pathological mechanisms of individual scars and adjust treatment protocols accordingly. (24, 26-31) Additionally, B-mode ultrasound is commonly used as the basis for other imaging methods, such as colour Doppler ultrasound or elastography, which can allow quantification of additional scar characteristics, such as their elastic properties. (26-29, 32, 33)

Despite the clinical advantages of B-mode ultrasound for scar thickness measurement, methods are poorly reported and lack standardisation in the literature. This casts doubt on the validity of clinical decision-making in measurement-based care initiatives (e.g., setting depth of AFCO$_2$ penetration) informed by research findings (e.g., response to treatment) where ultrasound measurements are used. (34) Lack of standardisation also makes between-study comparison, such as systematic reviews and meta-analyses, difficult, (35) and poor methodological reporting hampers the ability to accurately replicate findings. This scoping review focusses on mapping and identifying gaps in ultrasound methods and evaluation reported in the current literature along the research-to-clinical practice pipeline. (36) Methodological considerations for people performing ultrasound scar thickness measurements, including practitioners (herein termed assessors) using ultrasound in clinical practice are presented based on the review findings.

METHODS:

Protocol Publication and Review Structure:

The protocol for this review has been published *a priori*. (37) This scoping review was conducted and is reported according to the Arksey and O'Malley (2005) (38) framework. The steps outlined in this framework are: 1) identifying the research question; 2) identifying relevant records; 3) selecting appropriate records; 4) charting extracted data; and 5) collating, summarising and reporting the results. (38)

Research Question:

The primary question of this scoping review was: “What do we know and not know about the measurement of traumatic cutaneous scar thickness using ultrasound?” This question was addressed through exploration of: methods used; reliability and measurement error; clinical, health service, implementation and feasibility outcomes; factors influencing ultrasound imaging and measurement methods; strengths and limitations of measurement methods; and use of measurement guidelines and/or frameworks. While the focus of this review was the measurement of traumatic cutaneous scar thickness with ultrasound, methods used to measure the thickness of unscarred skin were reported where these were used in combination with measurement of scar thickness (e.g., as control or comparator measurements).

Identifying Relevant Records:

A standardised search strategy was developed and piloted with the assistance of a medical librarian using the concepts ‘ultrasound’, ‘skin’, ‘thickness’ and ‘measure’, with associated terms and truncations (supplementary box 1). Ovid MEDLINE, Embase, Cumulative Index of Nursing and Allied Health Literature (CINAHL) and Web of Science electronic databases were searched from conception to identify original studies (date last searched 27th May 2022).

The phrase ‘ultrasound scar thickness measurement’ was used to conduct additional searches in 1) Google Scholar, and 2) Google to identify original studies in grey literature, and studies not identified in database searches. Title and abstract searches in Google Scholar and Google were limited to the first 200 results. (39)

Record Selection:

Following de-duplication, six reviewers screened records using Covidence (Veritas Health Innovation, Melbourne, Australia; available at www.covidence.org) for eligibility according to the inclusion criteria (Table 1). Both peer-reviewed journal articles and abstracts were included to ensure that all the available and most recent methodological information was obtained. (40) Data collected from peer-reviewed journal articles was considered the primary source of data, with information from abstracts used to confirm or extend the journal data. The inclusion of abstracts will assist future authors to further investigate the information presented as full texts may become available. During both title and abstract and full text screening, one researcher (BM) screened all records as a single reviewer, while other researchers (MS, TM, TR, BD and ZT) screened records as a second reviewer. Conflicts were resolved through discussion between at least two authors to reach agreement. A third author was used as a tiebreaker where agreement could not be reached.

Table 1. Inclusion and exclusion criteria for studies included in the scoping review.

Inclusion	Exclusion
• Traumatic scars measured with ultrasound based on B-mode ultrasound (including high-frequency, ultra-high-frequency and Doppler) • Measurements taken of living, human individuals • Measurement of traumatic cutaneous scarring arising from penetration of the skin with sharp objects (including surgery or vaccination), or as a result of burns, (including thermal, chemical or friction) • Articles written in English, or with English abstracts	• Reviews, discussion papers, opinion pieces • Measurement of non-traumatic scars (e.g., acne scars). Non-traumatic scars measured along with burn scars were included • Measurement of skin thickness in non-traumatic conditions (e.g., diabetes) • Measurement of skin thickness where there is no cutaneous involvement in the trauma (e.g., traumatic brain injury) • Measurement using A-mode ultrasound

Charting the Data:

The data extraction table was developed in Microsoft Excel and piloted by two authors (BM and ZT) through independent extraction and comparison of data from two records. The table was then modified to include the scar characteristics (e.g., fibrosis, oedema) measured, measurer/assessor training, the number of measurements taken and funding sources

(Supplementary Table 1). Full text data extraction was completed by four authors (BM, MS, TM and ZT). An additional author (BD) independently extracted data from five randomly selected records, which was compared to data extracted by other authors. Minimal differences between data extracted by the independent author and that by other authors were observed, thus further independent extraction was not performed. As is typical in scoping reviews, the certainty or quality of evidence was not appraised. (38)

The research-to-practice pipeline published by the Australian Government Department of Health and Aged Care Medical Research Future Fund (figure 1) was used to categorise each included record based on their stated aims into one of the four phases. (36) Studies related to phase 1 of this pipeline, basic research, were only included in this review when data on scar or skin thickness pertained to human participants (table 1). Phase 2 of this pipeline included randomised controlled trials, while phase 3 included pragmatic and observational studies conducted outside randomised controlled trials. The final phase of this pipeline (phase 4) indicates initiatives used in routine clinical practice.

Where clinical (e.g., treatment satisfaction, scar symptoms), health service (e.g., efficiency, safety, effectiveness, equity, patient-centredness and timeliness) and implementation (e.g., acceptability, adoption, appropriateness, fidelity, cost, penetration and sustainability) outcomes were addressed, they were reported and defined according to Proctor *et al*. (41). For example, in the context of this scoping review, acceptability is defined as the level to which ultrasound is palatable amongst stakeholders (e.g., assessors), appropriateness is the perceived fit of ultrasound within regular clinical practice, and fidelity is the degree to which ultrasound is used in the way it was initially described. (41) Measurement instrument-specific feasibility outcomes defined by Prinsen *et al*. (42) are reported in the current review. These outcomes included ease of administration, standardisation, completion time, instrument cost and availability, and ease of score calculation. (42) Reliability and measurement error were defined according to COnsensus-based Standards for the selection of health Measurement INstruments (COSMIN) tools. (43, 44) Measurements with an intraclass correlation coefficient (ICC) of 0.7 or greater were considered reliable. (44) Measurement error was assessed by comparing the reported standard error of the measurement (SEM) with the reported smallest detectable change (SDC). Where the reported measurement error was smaller than the reported smallest detectable change, it was interpreted as indicating real change or variance can be detected, and that change or variance is not a result of error. (44)

Patient and Public Involvement

There was no patient and/or public involvement in the design, conduct, reporting or dissemination of information in this scoping review.

RESULTS:

Electronic database searches identified 9309 records. After removal of 3703 duplicate records, the titles and abstracts of 5606 records were screened for relevance according to the inclusion criteria (Table 1). Following full-text screening, 104 records proceeded to data extraction. Searches in Google and Google Scholar identified an additional 14 records, providing a total of 118 records for data extraction. Search and screening results are presented according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram (supplementary figure 1). (45)

Record Characteristics:

Of the 118 records included in this review, 82 were journal articles (69%) and 36 were abstracts (31%) (Table 2), representing a total of 5213 participants (range 1-438; mode 20 participants per record). Adults aged 18 years and older were most commonly targeted in articles (n = 43 articles; 52% of articles), (17, 26, 29, 46-85) while most abstracts did not report the age group measured (n = 25 abstracts; 69% of abstracts). (86-110) The most common scar type measured was burn scars in both journal articles (n = 43 articles; 52% of articles), (17, 22-24, 27, 47, 57-59, 61, 62, 64-67, 71-75, 81, 82, 84, 111-130) and abstracts (n = 23 abstracts; 64% of abstracts) (28, 30, 86-88, 91-94, 96, 98, 102-106, 131-135) (Table 2). Most identified articles used ultrasound measurement of scar thickness as part of research initiatives, and were categorised as either phase 2 (n = 50 articles; 61% of articles) (17, 22, 26, 31, 46-49, 51-56, 61, 63-65, 67, 69-71, 74-76, 78, 81, 83, 84, 111, 112, 114, 115, 117, 124-127, 129, 130, 136-145) or phase 3 (n = 30 articles; 37% of articles). (23, 24, 27, 29, 50, 57-60, 62, 66, 68, 72, 73, 77, 79, 80, 82, 85, 116, 118, 120-123, 128, 146-149) on the research-to-practice pipeline. (36) Phase 2 was also the most common phase represented by abstracts (n = 21; 58% of abstracts), (86, 88, 91, 93, 95, 97, 99-104, 106-108, 131-134, 150, 151) followed by phase 3 (n = 15 abstracts; 42% of abstracts). (28, 30, 87, 89, 90, 94, 96, 98, 105, 109, 110, 135, 152-154) Phase 4 was addressed by two articles (2% of articles) (113, 119) and one abstract (2% of abstracts), (92) which used ultrasound to measure treatment response to an intervention already used in routine clinical practice, including compression garments (113, 119) and CO_2 fractional laser. (92) No records pertained to phase 1.

Table 2. Summary of characteristics of records included in this review*

Characteristic	Category	Number of Records (Translational Pipeline Phase 2*)	Number of Records (Translational Pipeline Phase 3*)	Number of Records (Translational Pipeline Phase 4*)
Journal Articles				
Funding Source	Commercial	2	1	1
	Non-commercial	23	13	0
	Commercial & Non-commercial	2	1	1
	No funding	6	3	0
	Not reported	16	12	0
Population Type	Adult	27	16	0
	Paediatric	6	4	0
	Paediatric and Adult	13	7	2
	Not reported	3	3	0
Scar Aetiology	Burn	22	18	1
	Surgical†	5	2	0
	Mixed	10	3	0
	Not specified	12	7	0
Abstracts				
Funding Source	Commercial	0	0	0
	Non-commercial	3	1	0
	Commercial & Non-commercial	0	0	0
	No funding	0	0	0
	Not reported	17	14	1
Population Type	Adult	1	2	0
	Paediatric	0	3	0
	Paediatric and Adult	4	1	0
	Not reported	15	9	1
Scar Aetiology	Burn	12	10	1
	Surgical†	1	2	0
	Mixed	2	1	0
	Not specified	5	2	0

Legend: Paediatric: measurement of patients under the age of 18; Adult: measurement of patients aged 18 years or older; Burn: scars caused by thermal, chemical or friction injury; Surgical: scars caused by surgical procedures (including biopsies); Mixed: scars of included record were of mixed origin (e.g., burn and acne)

Footnotes: *Stage in the research to clinical practice translational pipeline, as defined by the Australian Government Department of Health and Aged Care (36); †Type of surgery defined in supplementary table 2

* A breakdown of each characteristic per record is presented in Supplementary Table 2

Methods used to measure traumatic cutaneous scar thickness:

B-mode, including high-frequency (i.e., ≥ 20 MHz) B-mode ultrasound was the most commonly reported ultrasound type used in both articles (n = 56; 68% of articles) (17, 22-24, 26, 29, 31, 46-49, 53, 54, 56, 57, 59, 60, 64, 65, 67, 69-78, 80-82, 84, 85, 111, 112, 114, 116-118, 120, 122, 123, 126-130, 138, 139, 141, 142, 144-146, 149), while most abstracts did not report the type of ultrasound used (n = 22; 61% of abstracts) (86, 87, 92-98, 101, 103, 105, 106, 108, 131-134, 150-153) (Table 3). Specialised B-mode ultrasound devices, including the Tissue Ultrasound Palpation System (TUPS; a B-mode ultrasound transducer in-series with a load cell to allow measured compression of the skin), (68, 99, 100, 124) and colour Doppler ultrasound, (52, 149) were used in six records (Table 3).

12 **Table 3. Summary of measurement methods used in included record***

Characteristic	Parameters	Number of Records
Journal Articles		
Ultrasound Type	B-mode	24
	Midrange	2
	High-frequency	29
	Other	4
	Not reported	22
Measurement Parameters	Epidermal	0
	Dermal	4
	Epidermal & dermal	2
	Combined epidermal & dermal	32
	Other	3
	Not reported	40
Scar characteristic measured	Fibrosis	27
	Oedema	1
	Fibrosis & oedema	10
	Other	1
	Not reported	42
Abstracts		
Ultrasound Type	B-mode	3
	Midrange	0
	High-frequency	9
	Other	3
	Not reported	21
Measurement Parameters	Epidermal	0
	Dermal	1
	Epidermal & dermal	4
	Combined epidermal & dermal	1
	Other	1
	Not reported	29
Scar characteristic measured	Fibrosis	2
	Oedema	0
	Fibrosis & oedema	0
	Other	0
	Not reported	34

Legend: B-mode: brightness-mode ultrasound (<20 MHz); High-frequency: High-frequency B-mode ultrasound (>20 MHz); Other: fields are expanded with additional detail in supplementary table 3

13 *A full summary of each included record is available in supplementary table 3

The type of scar and skin thickness measurement (i.e., thickness of the dermis, epidermis, or combined epidermal and dermal measurement) was reported in 39 records (33%) (Table 3). Where reported, combined measurement of epidermal and dermal thickness was the most common method used in articles (n = 32; 76% of articles reporting skin measurement type). (17, 22-24, 27, 29, 50, 53, 56-58, 60, 64-66, 70, 72-77, 80-82, 114, 116, 118, 122, 126, 127, 130, 139, 146, 148) Separate epidermal and/or dermal thickness measurements were reported in seven journal articles (17% of articles reporting skin thickness measurement type). (26, 47, 48, 52, 53, 71, 118) Of these records, two authors provided a rationale for this decision: each skin layer provided different information on the scar; (26) or responded differently to treatment. (67, 71) Most abstracts did not report the type of skin measurement used (n = 30; 83% of abstracts). (28, 30, 91-101, 103-110, 131-134, 150-154)

Three articles (4% of articles) (47, 110, 111) and one abstract (3% of abstracts) (28) directly reported that fibrosis was the scar characteristic targeted by the measurement. One of these records also quantified hair follicle density to assess the difference between scared and unscarred skin. (47) An additional 25 articles (30% of articles) (17, 46, 52, 53, 56, 63-65, 67, 70, 79, 80, 83, 84, 112, 120, 123, 125-127, 140, 142, 145, 148, 149, 155) and one abstract (3% of abstracts) (110) made indirect reference (i.e., within the introduction or discussion) to the measurement of fibrosis. Ten journal articles (12%) made indirect reference to the measurement of both oedema and fibrosis, (31, 54, 55, 71, 74, 76-78, 138, 144) and one record made indirect reference to the measurement of oedema. (59)

Additional objective and/or subjective measurement methods were employed alongside ultrasound measurement in 72 articles (88% of articles) (17, 22, 24, 26, 29, 31, 46-53, 55-57, 60-70, 72-81, 83-85, 111-122, 124-130, 136-142, 144, 145, 147-149) and 31 abstracts (86% of abstracts) (86, 88, 89, 91-95, 97-110, 131-134, 150, 151, 153, 154) (Supplementary Table 4). All three phase 4 studies involving implementation in routine clinical practice utilised additional measurements. (92, 113, 119) The additional objective measurements used in included records were elastography (elasticity), cutometric assessment (pliability) and Doppler ultrasound (vascularity). The additional subjective measurements were conducted using clinician-based rating scales (e.g., Vancouver Scar Scale or modified Vancouver Scar Scale) or Patient Reported Outcome Measures. The Vancouver Scar Scale was used in 35 articles (43% of articles) (17, 31, 46, 47, 49, 50, 52, 55, 57, 61-64, 66-70, 73, 85, 111, 112, 114, 116, 118, 121, 124, 128, 130, 136-138, 140-142) and 11 abstracts (31% of abstracts) (88, 91, 92, 98-100, 107, 134, 150, 151, 153). Patient-reported outcome measures (PROMs) were used in 27 articles (33% of articles) and 11 abstracts (31% of abstracts). (46, 53, 56, 57, 60, 72-75, 85, 91, 94, 97, 101-106, 111, 112, 114, 115, 117, 118, 120, 122, 129, 131-133, 138, 140, 141, 148, 150, 151, 153, 154) Of the records that reported using PROMs, the most commonly used was the patient report of the Patient and Observer Scar Assessment Scale (POSAS), used in 17 articles (63% of articles reporting use of PROMs) (17, 22, 46, 50, 53, 61, 62, 64, 76, 77, 79, 114, 121, 125-127, 147) and 8 abstracts (73% of abstracts reporting use of PROMs) (91, 93, 102, 104, 106, 132, 153) (Supplementary Table 4). In most cases, additional measurement methods were used to supplement ultrasound thickness measurements as research outcomes. In some records (n = 16; 14% of records), however, ultrasound was compared with histology, POSAS, dermoscopy, VSS and modified VSS, clinical assessment, modified Seattle Scar Scale, high-definition optical coherence tomography, 3D camera, immunohistochemistry, and immunohistomorphometry. (17, 24, 26, 29, 31, 50, 51, 64, 73, 77, 86, 95, 110, 120, 124, 149) Where the effectiveness of ultrasound was judged against other methods, it was only found to be inadequate against histology. (26, 86)

Methods used to relocate the scar for repeated measurements were reported in 34 records (29%) (Supplementary Table 3). The most common relocation method was tracing the outline or boundaries of the scar on a transparent or translucent sheet (n = 14 articles; 35% of articles reporting scar relocation), (23, 49, 65, 74, 81, 115, 116, 120, 124, 125, 153) occasionally including prominent or bony landmarks close to the scar. (23, 24, 72, 73, 123) Photographs (n = 10 articles; 25% of articles reporting relocation and n = 1 abstract) and linear measurements from defined points or anatomical landmarks on or around the scar (n = 4 articles; 10% of articles reporting relocation) were also used for scar relocation. The 'worst' or 'thickest' part of the scar, as determined by patients or assessors, was chosen as the measurement site in 14 journal articles (35% of journal articles reporting relocation) (23, 31, 52, 54, 57, 61, 62, 67, 126, 127, 138, 141, 148, 155) and one abstract. (105)

Measurement of unscarred skin, either contralateral or adjacent to the scar, was performed in 32 articles (39% of articles%) (17, 22-24, 27, 29, 46-48, 50, 51, 53, 56-60, 64, 72, 73, 80, 81, 85, 114, 118, 120-122, 128, 145, 146, 148) and 7 abstracts (19% of abstracts) (28, 94, 95, 150, 151, 153, 154) These measurements were primarily used as controls or comparators to scar measurements (n = 27, 69% of records reporting unscarred skin measurement). (17, 22, 23, 28, 29, 47, 48, 51, 53, 56-60, 64, 67, 73, 80, 85, 95, 118, 120, 122, 128, 146, 148, 153, 154) Additionally, four records (10% of records reporting unscarred skin measurement) evaluating treatment efficacy measured both unaffected skin thickness and the thickness of a 'control' or untreated scar. (46, 74, 94, 114) All instances where additional ultrasound measurements were taken of unscarred skin or untreated scars were reported as part of research initiatives aligning with phases 2 and 3 of the research-to-practice pipeline (figure 1). (36)

Reliability and measurement error

Reliability was calculated for both scarred and unscarred skin in 13 articles (16% of articles) and two abstracts (5% of abstracts), and was generally considered acceptable (Supplementary

Table 5). This included inter-rater reliability (n = 5; 4% of articles), (54, 64, 73, 120, 137) intra-rater reliability (n = 3; 4% of journal articles), (22, 23, 65) and both inter- and intra-rater reliability (n = 7; 6%; including 2 abstracts) (17, 24, 57, 82, 87, 105, 124). The intraclass correlation coefficient (ICC) was the most commonly reported reliability statistic (n = 10; 8% of records, including one abstract), (17, 24, 57, 64, 65, 73, 82, 87, 120, 124) where it was reported for both scar and unscarred skin measurements in four articles (5% of articles). (17, 24, 57, 73) The reported combined thickness (i.e., epidermal and dermal) ICCs for inter-rater reliability of scarred skin ranged from 0.82 to 0.985, while the inter-rater ICC for the measurement of unscarred skin ranged from 0.33 to 0.98, with one of the four records reporting an ICC below the threshold value of 0.7 (ICC = 0.33) (24) and one record simply reported that the inter-rater ICC for scarred skin was “acceptable to high”. (64) The reported intra-rater reliability for combined thickness measurements of scarred skin ranged from 0.89 to 0.983, and for unscarred skin ranged from 0.61 to 0.982, with one record reporting an ICC below the threshold of 0.7 (ICC = 0.61). (24) One record reported both the inter- and intra-rater ICCs for individual epidermal (inter-rater ICC = 0.297; intra-rater ICC = 0.809) and dermal (inter-rater ICC = 0.991; intra-rater ICC = 0.991) scar thickness measurement. (87) Four articles (5% of articles) reporting reliability used Pearson’s R, an undisclosed method, or description (e.g., high) as detailed in supplementary table 2. (22, 54, 105, 137)

Measurement error for inter-rater and intra-rater reliability of combined, epidermal or dermal thickness was reported in four articles (5% of articles) and one abstract using standard error of the measurement (SEM). The inter-rater SEM for the combined epidermal and dermal thickness of scarred skin ranged from 0.11 mm to 0.5 mm, and the intra-rater SEMs ranged from 0.18 to 0.52 mm. Individual records reported SEM values for unscarred skin, and separate epidermal and dermal measurements, available in Supplementary Table 5. (17, 23, 24, 82, 87) Only one record reported calculation of the smallest detectable change (SDC). In that record the inter-and intra-rater SDC was calculated for both scarred and unscarred skin. The scarred skin SDCs were 1.4 mm (inter-rater) and 0.6 mm (intra-rater), and unscarred skin SDCs were 0.8 mm (inter-rater) and 0.5 mm (intra-rater). (24) The reported SEMs were all close to or below the largest SDC value reported. This finding may indicate that ultrasound can detect true variance in scar thickness above measurement error for traumatic scar and skin thickness.

Of the records that reported reliability and measurement error, measurements were taken by practitioners with varying clinical expertise and roles within the treating team. These included therapists, nurses and doctors, sometimes under the supervision of trained radiologists. One record reported that 3 assessors received 3 hours of training, and conducted 10 assessments using the study protocol before the study began. (57)

Clinical, health service, implementation and feasibility outcomes:

No record specifically investigated clinical, health service, implementation or feasibility outcomes of ultrasound as a measurement-based-care initiative. Ultrasound was used to assess the clinical outcomes of scar treatment initiatives in all included records. Clinical, health service, implementation and feasibility outcomes related to ultrasound measurement were, however, reported in 53 journal articles (17, 22-24, 26, 27, 31, 46-48, 50, 51, 54, 56-61, 63-66, 69-75, 77, 80, 82, 113-116, 119, 120, 122-124, 128, 129, 138, 142-144, 148, 149, 155) and 14 abstracts (28, 86, 87, 89, 90, 95, 96, 102, 105, 107, 109, 110, 152, 153) that focused on scar treatments.

The clinical outcome of patient satisfaction related to ultrasound measurement was only reported in one journal article. Whilst patient satisfaction was not directly measured in that record, a proxy measure of satisfaction was reported by the authors stating that no paediatric patient or their caregiver refused ultrasound measurement once the purpose was explained. (24)

Timeliness was the only reported health service outcome, reported as the time required to take ultrasound measurements. Where reported in three journal articles, this was short, taking between one to five minutes. (24, 27, 122)

The most common implementation outcomes reported in the identified records were fidelity, acceptability and appropriateness. Fidelity to the measurement method was reported through the use of experienced or trained assessors (n = 6 journal articles; n = 1 abstract), (24, 57, 58, 87, 142, 144, 148) and/or utilising the same assessor/s for all measurement sessions (n = 5 journal articles; 6% of included journal articles). (24, 61, 138, 144, 148) Differences between intended and actual measurement methods were not discussed. The training and/or experience of the assessors was discussed in 24 records (23 journal articles and 1 abstract), (17, 23, 24, 27, 51, 56-59, 63-66, 71, 73, 115, 116, 120, 123, 124, 138, 144, 149, 153) where measurements were either taken by a clinician (n = 13; 54% of records reporting training), (17, 23, 24, 58, 59, 64-67, 71, 120, 124, 141) members of the research team (n = 6; 25% of records reporting training), (57, 63, 73, 115, 123, 144) or by specialist sonographers and/or radiologists (n = 5, including one abstract; 21% of records reporting training). (56, 116, 138, 149, 153) Only one record reported on fidelity in the context of routine clinical practice. In this instance, ultrasound was conducted in the department of radiology, however the role or training of the staff was not reported. (119)

The acceptability and appropriateness of the ultrasound methods used in individual records were generally based on author opinion and outlined in the discussion. Acceptability was reported in 26 records (23 journal articles and 3 abstracts), (17, 22-24, 26-28, 31, 57, 64, 70, 74, 75, 77, 80, 82, 86, 96, 116, 119, 120, 122, 124, 143, 149, 155) including for paediatric populations, where one record reported potential difficulty in measuring this population, (22) contrasting that which reported that measurement was acceptable to both children and their caregivers. (24) One record reported acceptability where the intervention being analysed by ultrasound was already part of routine clinical practice. In this instance, the authors referenced additional publications which stated that ultrasound had an accuracy of 0.5 mm, which was judged by the authors to be sufficient for assessment of scar thickness. (24, 27, 119, 122) Potential difficulty was identified in the measurement of open wounds, (24) and traditionally hard-to-reach areas (such as the axillae or groin). (22)

The appropriateness of the ultrasound methods was reported in 35 journal articles (43% of included journal articles) (22, 24, 26, 27, 31, 46-48, 50, 54, 57, 60, 61, 64-66, 69, 72-75, 77, 80, 82, 113, 114, 116, 119, 120, 122, 124, 128, 148, 149, 155) and 11 abstracts (31% of included abstracts) (86, 87, 89, 90, 95, 102, 105, 107, 109, 110, 152), where it was generally addressed in the discussion. Of these records, two (4% of records reporting appropriateness) determined that ultrasound was not appropriate for scar measurement. The first stated that it was too inaccurate and complex; (86) and the second, which reported on initiatives within routine clinical practice, determined that the minimum resolution of the Diasonography ultrasonic scanner (Nuclear Enterprises, Edinburgh, UK) precluded its use in scars thinner than 3mm. (113)

The feasibility of ultrasound was reported in 12 journal articles (15% of included journal articles). (22, 24, 26, 46, 57, 70, 80, 119, 120, 124, 129) Five records considered ultrasound not feasible for scar measurements. The rationale presented included high-frequency 20 MHz ultrasound having an inadequate penetration depth; (26, 57) and ultrasound measurement and training of investigators requiring too much time (as reported in one record in phase 4 of the research-to-practice pipeline). (22, 119, 120) Another factor identified as precluding feasibility was the inability to consistently relocate the measurement site. (24) Conversely, one record reported ultrasound to be feasible in combination with Vancouver Scar Scale (VSS) measurement, (70) and another stated that ultrasound was able to distinguish between subcutaneous fat and muscle, which was interpreted by the authors of that record to mean that skin thickness measurements were accurate. (129) The majority (n = 11; 92%) of the records reporting feasibility were research initiatives in phase 2 or 3 of the research to practice pipeline. One record examined feasibility in the context of routine clinical practice (i.e., phase 4; figure 1), (119) where it was determined that ultrasound was not suitable for use in their twelve-year longitudinal study due to changes in staff, equipment and software over such a long time period, which introduced additional variables to the measurement process that were impossible to control. (119)

Factors influencing ultrasound images and measurement methods:

The only factor that was reported to influence the imaging and measurement methods was the measurement of scars with open wounds. This was reported in one record, which determined that ultrasound and ultrasound gel was unsuitable in this instance. The authors of that record suggested the use of a flexible transparent plastic wrap, which is placed over the measurement area prior to measurement with ultrasound. (24)

Reported strengths and limitations of the measurement methods:

The safety, practicality, objectivity, versatility, reliability and non-invasive nature of ultrasound were all reported as strengths of the measurement method. (22, 27-29, 47, 50, 57, 61, 64, 77, 78, 80, 82, 87, 89, 95, 96, 105, 107, 109, 119, 123, 124, 129, 139, 148) When compared to other subjective or clinical measurement methods (e.g., VSS) and 3D camera, ultrasound was viewed as the superior measurement method of scar and skin thickness, due to its improved accuracy, greater sensitivity to change and objectivity. (24, 64, 73, 116, 120) The ability of ultrasound to differentiate between scarred and unscarred skin was also highlighted (n = 4; 3%), (47, 60, 72, 122) as was the versatility of ultrasound in its ability to measure a variety of anatomical areas and be used with child participants (i.e., <18 years) (n = 2; 2%). (22, 149)

The poor correlation between ultrasound and histological thickness measurements, (86) and the established inverse relationship between ultrasound penetration depth and the resolution of superficial structures were identified as limitations of ultrasound in the measurement of scar thickness. (26, 27, 77, 80, 89, 113, 149) This may be an evidence gap worth exploring in more depth. One record, reporting on a longitudinal study that was conducted over twelve years, reported that the continuous development of ultrasound software and hardware over that time limited the usefulness of ultrasound. (119) Despite being reported elsewhere as acceptable (i.e., between one to five minutes (24, 27, 122)), one record reported that the time-consuming nature of measurement and the requirement for assessors to be trained in the operation of, and techniques required for, ultrasonography was a limitation of the method. (120) Methodologically, concerns were raised around the pressure caused by application of the ultrasound transducer to the skin, and how that may influence thickness measurement. (61, 62, 123, 124) The size of the transducer head relative to the size of scars was also considered a potential limitation, as multiple measurements are required for quantification of larger scars. (57) Finally, it was recognised that there may be a difference between changes to the scar that can be measured by ultrasound, and what is felt and/or experienced by the patient. (75, 80, 126, 127) It was suggested that changes that are detectable by ultrasound may be smaller than those able to be detected by patients. In patients with burn scars, a minimum change in scar thickness of between 1 to 6 mm measured by ultrasound, has been reported to be required before a patient may report noticing any difference to their scar thickness. (24, 75) While further research is required to allow generalisation of these findings to other scar aetiologies, this indicates that a holistic approach to scar thickness using the patient's opinion as well as objective measurement through ultrasound may be beneficial.

Guidelines or frameworks used to guide the measurement methods:

No records reported using any guidelines or frameworks to inform their measurement methods. One record utilised suggestions from The American Wound Healing Society to support the measurement of contralateral, unscarred skin thickness on the same individual as a control or comparator. (75)

Methodological Considerations:

Based on the ultrasound methods and outcomes identified in this review, a list of methodological considerations have been compiled (Supplementary Table 6). These are intended to guide the decision-making and methodological reporting of researchers and/or clinicians undertaking scar or skin thickness ultrasound measurement.

DISCUSSION:

This review mapped the methods used in the published literature to measure traumatic scar thickness using ultrasound across the research-to-practice translational pipeline. No record reported their methods with sufficient detail to allow them to be independently replicated. Overall, there was a lack of consistent rationale underpinning which skin layers (i.e., epidermis, dermis and combined) were measured, and little consideration was given to the training and experience required by assessors. The included records mainly aligned with the second and third phases of the research-to-practice pipeline (figure 1), with only three records (2 articles and 1 abstract) reporting the use of ultrasound in routine clinical practice (phase 4). (92, 113, 119). The paucity of records aligning with phase four studies (use in clinical practice) suggests a translational gap from research to regular clinical practice. There are two likely explanations for this: 1) that ultrasound is most commonly used as an outcome measure for research initiatives and is not regularly used to evaluate care once treatments are implemented into routine clinical practice; or 2) that use of ultrasound in routine clinical practice is not reported or evaluated, as routine clinical practice is rarely published.

Searching of grey literature was conducted in an attempt to identify clinical practice documents, however none were located. Surveys of health service departments may be the best method of identifying ultrasound methods used in regular clinical practice as part of future research. While some records reported using additional subjective and objective measurement methods in addition to ultrasound, none used these methods to determine the criterion validity of the ultrasound for scar thickness measurement. This is another evidence gap that should be addressed.

While efforts have been made to standardise ultrasound measurement procedures elsewhere in dermatology (including tumours, cancers, vascular anomalies, and systemic sclerosis (34, 35)), this same effort has not yet extended to the measurement of traumatic scarring. Methodological standardisation has the potential to increase confidence in the use of ultrasound as the basis of measurement-based care initiatives for clinical decision-making, allowing patient care and scar treatments to be tailored towards individual needs. (62, 147, 156) Standardising the core methodological components of ultrasound measurement of scar thickness, or at the very least, creating a standardised framework for methodological decision-making, may support implementation of ultrasound measurement into routine clinical practice, supported by strategies to overcome barriers to implementation at local sites. (157)

This review identified novel insights into the identification of the composition of cutaneous scars using ultrasound, and highlighted the apparent lack of consistent understanding of, or rationale behind, what scar thickness characteristics were being measured. Fibrosis is generally understood to be the primary cause of scar thickness through the deposition of excessive extracellular matrix proteins such as collagen. (158, 159) This has been confirmed through histological analysis, which has shown the presence of excess collagen and other extracellular matrix proteins in the dermis of hypertrophic scars. (160, 161) An additional method for assessing the effects of scarring on the dermis, as identified by one record in this review, (47) is through quantification of the presence and density of hair follicles. This quantification may serve as a method of differentiation between scarred and physiological skin, and may also serve as a measure of skin function. (47) What is less understood, and perhaps largely overlooked, is the function of the epidermis in scar thickness. In the one record identified in this review that directly report the measurement of the epidermis, the authors noted that the measurement quantified the presence of oedema. (55) This was further supported by two records that noted that the epidermis and dermis responded differently to treatment, (67, 71) indicating that there is likely a difference in the composition of the scar between these skin layers. Cutaneous oedema has been observed using high-frequency ultrasound in other pathologies, including atopic dermatitis and skin ageing, where it is characterised by the presence of a sub-epidermal low echogenic band (SLEB), a hyperechoic band at the dermoepidermal junction. (162) Understanding the interplay between epidermal oedema, dermal fibrosis and the presence and density of hair follicles may result in an increased understanding of the mechanisms and treatment responses of cutaneous scarring. With better understanding, more targeted scar treatments that inform a greater understanding of scar responsivity may arise.

Another important, but potential limiting factor for the use of ultrasound to measure scar thickness raised in this review is the training and/or experience required of assessors, and the ramifications this likely has on the reliability of measurements and interpretation. (163) This review identified 24 records where assessor experience was discussed, however none made any recommendations on the optimal training and/or experience. Identifying the training requirements of assessors may prove an important step towards more widespread implementation of reliable ultrasound scar thickness measurement in research trials and as the basis for measurement-based care in routine clinical practice. (164) A panel of dermatological and ultrasound experts has previously recommended that a physician with a minimum of 300 examinations per year should hold responsibility for ultrasound measurements. (34) It has also been suggested that training existing members of clinical teams and standardising measurement method/s may be the most effective way to achieve minimum reliability standards under clinical conditions. This could allow measurement to be reliably conducted within an outpatient clinic setting by a number of healthcare providers assisting workflow, negating the requirement for patients to wait for an experienced radiographer. (24, 164) In the current review, reliability estimates were generally acceptable but were tested under research conditions. The diverse experience and expertise of assessors, where reported for the reliability estimates, means that the acceptable reliability results should be generalisable to most clinical teams, as therapists, doctors and nurses were all included. The cumulative sample size of all reliability studies also supports this generalisation; however each team should perform their own reliability estimates before conducting ultrasound thickness measurements.

Study Limitations:

Only articles available in English or with an English abstract were considered for inclusion and data extraction, which may have resulted in the omission of eligible information. Data extraction was completed on the English abstracts of two non-English articles that were available electronically, however the non-English articles themselves were not available to the authors, and thus could not be analysed. Based on the number of records included in this review, however, it is unlikely that this would have impacted the review findings. It is acknowledged that methods reported in included abstracts may not be fully reproducible, due to their brevity. Thus, findings were reported separately to articles. An additional limitation was that authors of included records were not contacted to provide clarification or further information, as this was not feasible given the number of results identified. It should also be acknowledged that the included records were not designed to align with the specific aims of this review, which likely explains some of the lack of reporting on outcomes of interest in our review, particularly clinical, health service and implementation outcomes. Furthermore, as this review relied on published information (including grey literature), routine practices employed within organisations may not have been considered and unpublished industry sponsored reports may not have been identified.

It is also important to consider the limitations of ultrasound itself for the holistic quantification of cutaneous scarring. Ultrasound transducers are generally small, meaning that it is difficult to assess the entirety of a scar, necessitating multiple measurements. (165) Additionally, thickness is often not the only scar parameter of clinical or research interest. It has therefore been recommended that multi-modal measurement techniques are employed, which include both subjective and objective measurements. (166, 167) However, use of these methods may be challenging in routine clinical practice, due to the length of time and training required. Thus, feasibility and implementation outcomes are of importance in evaluating measurement-based care initiatives involving ultrasound alone or multimodal measurement tools in scar care practice – a field in its infancy based on this review.

Future Directions:

It is intended that the results of this review will be used to inform the creation of a Delphi consensus study, leading to the formation of a guideline for the measurement of traumatic scar thickness using ultrasound. This guideline can then be used by researchers and clinicians to standardise the measurement of scars. In preparation for this study, we have provided a list of methodological considerations for assessors or practitioners when planning to conduct scar thickness measurements with ultrasound (Supplementary Table 6). Future research could also investigate aspects that were beyond the scope of this review including factors influencing the implementation of ultrasound-based care initiatives, strategies to support implementation, and how research-based initiatives could be applied in practice. Further studies are needed that compare SDCs to SEMs to interpret reliability estimates to confirm our interpretation that ultrasound may have the ability to detect true change or variance in scar thickness above measurement error, which was based on the SDC reported by a single study. Our interpretation is supported by mostly acceptable reliability estimates of ultrasound thickness for other cutaneous conditions. (168, 169) Additional investigations should also be conducted to determine the criterion validity of ultrasound as a measure for scar thickness.

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The authors declare no competing interests. The research presented in this publication was conducted as part of BM’s PhD, and will be included in his thesis for submission to The University of Queensland.

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AUTHOR CONTRIBUTIONS

BM and ZT conceived the project after identifying this area as a knowledge gap in existing literature. BM developed the research questions and study methodology, conducted the literature search, screened all articles and extracted data. Record screening and data extraction was completed by BM, MS, TM, and TR, with additional extraction completed by BD to assess consistency. MS, TM, TR and RK provided advice to BM on the clinical implications of ultrasound measurement. MS, RK and ZT contributed to the supervision of BM as a PhD student. BM drafted the paper, and ZT and MS provided critical appraisal of the drafted manuscript, with further advice provided by TM, TR, BD and RK.

DATA SHARING STATEMENT:

Not applicable

ETHICS APPROVAL STATEMENT:

This study does not involve human participants. No ethics approval was required.

FIGURE LEGENDS:

Figure 1: Research to clinical practice pipeline.

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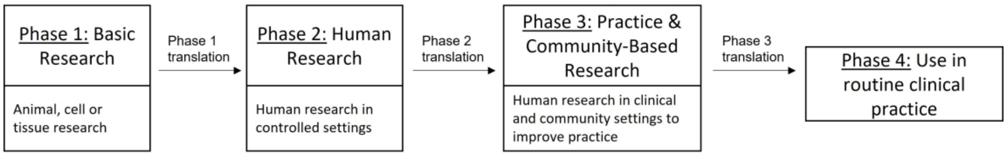


Figure 1: Research to clinical practice pipeline.

275x42mm (330 x 330 DPI)

Supplementary Box 1. Full search strategy for Ovid MEDLINE.

((ultrasound.ti,ab. OR ultra sound.ti,ab. OR sonograph*.ti,ab. OR ultrasonic.ti,ab. OR high-frequency.ti,ab. OR high frequency.ti,ab. OR hfus.ti,ab. OR ultrasonog*.ti,ab. OR exp Ultrasonography/)
AND

((skin.ti,ab. OR epiderm*.ti,ab. OR derm*.ti,ab. OR cutaneous.ti,ab OR scar*.ti,ab OR keloid*.ti,ab OR cicatri*.ti,ab OR exp Skin/ OR exp Dermatology/ OR exp Cicatrix/)

AND

(thickness*.ti,ab. OR thicken*.ti,ab. OR depth.ti,ab. OR volume.ti,ab. OR height.ti,ab. OR vancouver scar scale.ti,ab)

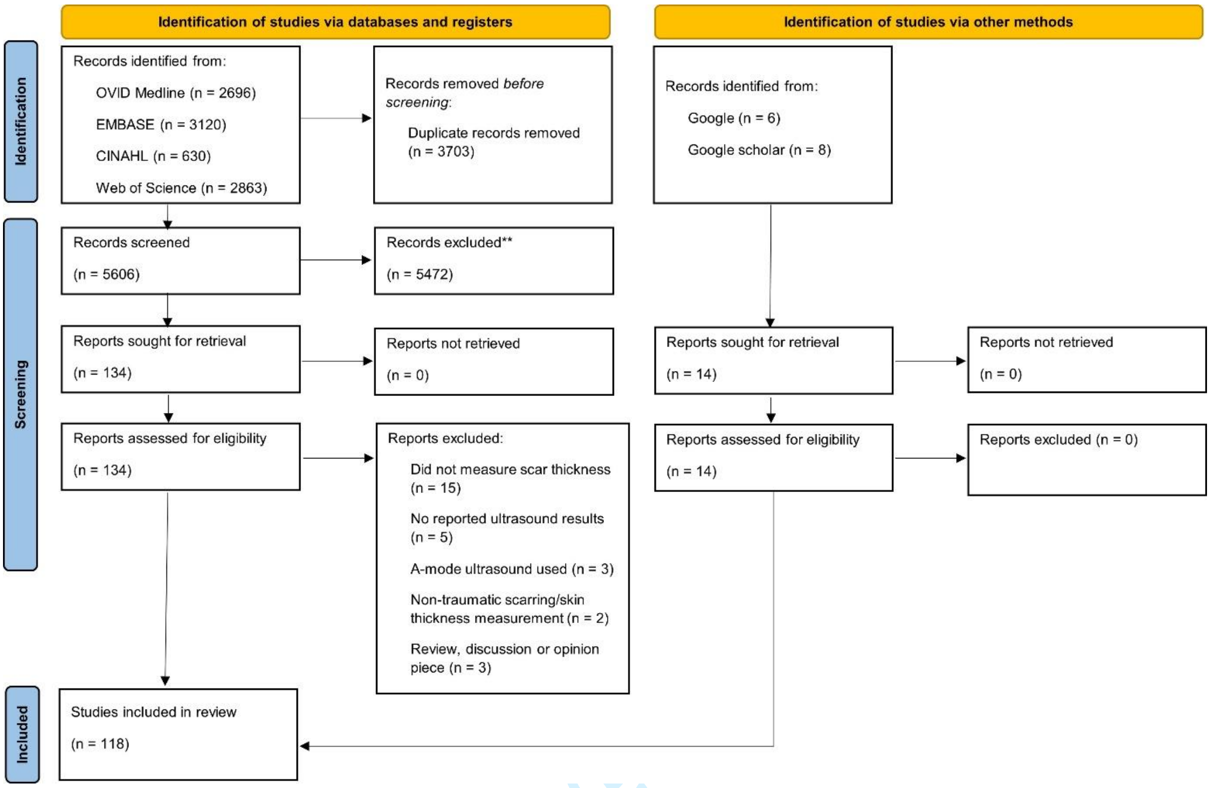
ADJ10

(measure*.ti,ab. OR quantif*.ti,ab. OR calculat*.ti,ab OR estimat*.ti,ab OR assess*.ti,ab. OR determin*.ti,ab. OR evaluat*.ti,ab OR imag*.ti,ab OR exam*.ti,ab)))

NOT (exp animals/ NOT exp humans/)

Legend: ab, abstract (searches the abstract of the publication); adj10, adjacency (search terms must be located within 10 words of one another); exp, explode (used to include all subheadings when searching MeSH headings); ti, title (searches the title of the publication)

Supplementary Figure 1. Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram for this study.



Supplementary Table 1: Extraction categories and fields

Extraction category	Extraction field
Publication details	First author
	Year of publication
	Title of publication
	Country (first author)
	Country (study)
	Country (recruited)
	Publication type (e.g., peer-reviewed journal article, abstract)
	Journal name
	Corresponding author contact details
	Funding source (e.g., commercial, non-commercial)
	Use of scar thickness measurement (e.g., longitudinal study, response to treatment)
Study details	Aim/objective
	Research questions
	Target population/topics
	Study design (e.g., RCT, mixed methods)
	Data and analysis (i.e., statistical methods)
	Removal of scar treatments before ultrasound measurement (e.g., length of time before measurement)
	Reason for measurement (e.g., research, clinical initiative)
	Inclusion/exclusion criteria
	Dates of data collection
	Ultrasound thickness collection methods (e.g., direct collection, collected from medical records)
	Contralateral/unaffected/comparator skin thickness measurement
	Other methods used
	Use of guidelines/frameworks for measurement methods
	How previously published methods/guidelines were used
	Research pipeline stage
	Setting (e.g., inpatient/outpatient clinics)
	Scar type (e.g., burn scar, surgical scar)
Participant details	Number of participants
	Population type (e.g., adult/paediatric)
	Gender ratio
	Patient involvement in thickness determination
	How patients were involved in thickness determination
Ultrasound methods	Ultrasound mode
	Device name and manufacturer
	Frequency used
	Number of measurements taken
	What did researchers report they were measuring (e.g., fibrosis, oedema)
	Anatomical locations/functional measurement units measured
	Patient orientation
	Ultrasound transducer orientation
	Methods used to prevent skin compression
	Measurement site relocation strategies
	Type of skin measurement (i.e., epidermis/dermis/combined)
	Measurer training
Psychometric properties[*]	Reliability
	Measurement error
Feasibility[†] outcomes	Time taken for measurement

	Availability of measurement method
	Ease of administration
	Number of steps required
	Number of people required to conduct measurements
	Considerations for special populations
Implementation[‡] outcomes	Acceptability
	Adoption
	Appropriateness
	Cost
	Feasibility
	Fidelity
	Sustainability
Strengths and limitations of measurement methods	Strengths
	Limitations
	Barriers
	Enablers
Findings	Ultrasound-related findings

[*] Psychometric properties as outlined in the COSMIN Risk of Bias tool to assess the quality of studies on reliability or measurement error of outcome measurement instruments[1]

[†] Feasibility outcomes as per Prinsen *et al*.[2]

[‡] Implementation outcomes as per Proctor *et al*.[3]

Supplementary Table 2. Characteristics of records included in this review. Studies are listed alphabetically by author within the translational pipeline phase.

First Author (year)	Country of Publication	Funding Sources	Sample Size (n)	Population Type	Scar Aetiology	Translational Pipeline Phase*
Journal articles						
Agabalyan (2017)	Canada	Non-commercial	10	Adult	Not specified	2
Alsharnoubi (2018)	Egypt	No funding	15	Paediatric	Burn	2
Alsharnoubi (2018)	Egypt	Not reported	15	Paediatric	Burn	2
Alshehari (2015)	Egypt	Not reported	30	Not reported	Mixed	2
Blome-Eberwein (2012)	United States	Non-commercial	16	Paediatric & adult	Burn	2
Blome-Eberwein (2016)	United States	Not reported	36	Adult	Not specified	2
Blome-Eberwein (2019)	United States	Non-commercial	19	Adult	Burn	2
Cai (2019)	China	Non-commercial	51	Adult	Not specified	2
Candy (2010)	Hong Kong	Not reported	17	Adult	Not specified	2
Chan (2004)	China	Non-commercial	56	Paediatric & adult	Burn	2
Chang (2014)	Taiwan	Non-commercial	60	Paediatric & adult	Surgical (cleft lip repair)	2
Cho (2014)	Korea	Non-commercial	146	Not reported	Burn	2
Deng (2019)	China	Not reported	20	Adult	Not specified	2
Deng (2021)	China	No funding	31	Adult	Not specified	2
Deng (2021)	Hong Kong and China	Non-commercial	45	Adult	Not specified	2
Dunkin (2007)	England	Non-commercial	113	Adult	Surgical (dermal scratch)	2
Elrefaie (2020)	Not specified	Not reported	22	Paediatric & adult	Not specified	2
Fabbrocini (2016)	Not specified	Not reported	20	Adult	Mixed	2
Fraccalvieri (2011)	Italy	No funding	5	Adult	Mixed	2
Fraccalvieri (2013)	Italy	Not reported	3	Paediatric & adult	Mixed	2
Gee Kee (2016)	Australia	Commercial	43	Paediatric	Burn	2
Issler-Fisher (2021)	Australia	Commercial	187	Adult	Burn	2
Joo (2020)	Korea	Non-commercial	48	Adult	Not specified	2
Lacarrubba (2008)	Not specified	Not reported	8	Paediatric & adult	Mixed	2

Lau (2005)	Hong Kong	Not reported	100	Paediatric & adult	Burn	2
Lee (2019)	United Kingdom	Non-commercial	55	Adult	Burn	2
Lee (2020)	United Kingdom	Non-commercial	55	Adult	Burn	2
Li (2013)	China	Non-commercial	7	Adult	Burn	2
Li (2020)	China	Not reported	21	Paediatric & adult	Mixed	2
Li (2021)	China	Non-commercial	165	Paediatric	Mixed	2
Li (2021)	China	Non-commercial	105	Adult	Burn	2
Li-Tsang (2006)	Not specified	Non-commercial	45	Adult	Not specified	2
Li-Tsang (2010)	China	Non-commercial	104	Paediatric & adult	Mixed	2
Mamdouh (2021)	Egypt	Not reported	40	Adult	Not specified	2
Meirte (2016)	Belgium	Non-commercial	9	Adult	Burn	2
Miletta (2021)	United States	Non-commercial	29	Paediatric & adult	Burn	2
Nedelec (2019)	Canada	Non-commercial	70	Adult	Burn	2
Nedelec (2020)	Canada	Non-commercial	51	Adult	Burn	2
Nicoletti (2015)	Italy	Not reported	27	Paediatric & adult	Surgical (scar reconstruction)	2
Niessen (1998)	The Netherlands	Commercial & Non-commercial	145	Paediatric & adult	Surgical (breast reduction)	2
Reinholz (2020)	Germany	No funding	25	Adult	Mixed	2
Schwaiger (2018)	Germany	No funding	15	Adult	Mixed	2
van den Kerckhove (2005)	Belgium	Not reported	60	Adult	Burn	2
van der Veer (2010)	The Netherlands	Non-commercial	44	Adult	Surgical (cardiothoracic surgery)	2
Wang (2009)	China	Non-commercial	22	Adult	Burn	2
Wiseman (2020, 2021)	Australia	Commercial & Non-commercial	153	Paediatric	Burn	2
Xuan (2021)	Not specified	Not reported	72	Not reported	Not specified	2
Yim (2010)	Korea	No funding	31	Paediatric & adult	Burn	2
Zadkowski (2016)	Not specified	Not reported	47	Paediatric	Burn	2
Avetikov (2018)	Not specified	Not reported	50	Paediatric & adult	Not specified	3

Chae (2016)	Korea	Non-commercial	23	Adult	Not specified	3
Cheng (2001)	Hong Kong	Not reported	58	Paediatric	Burn	3
Danin (2012)	France	Not reported	22	Paediatric & adult	Burn	3
Fong (1997)	Not specified	Not reported	16	Paediatric & adult	Burn	3
Gankande (2014)	Australia	Non-commercial	30	Adult	Burn	3
Ge (2022)	China	Not reported	21	Paediatric & adult	Mixed	3
Guo (2020)	China	Non-commercial	87	Paediatric & adult	Not specified	3
Huang (2017)	Taiwan	Not reported	1	Adult	Burn	3
Huang (2020)	China	Non-commercial	43	Adult	Not specified	3
Huang (2021)	Taiwan	Not reported	5	Adult	Burn	3
Issler-Fisher (2017)	Australia	No funding	47	Paediatric & adult	Burn	3
Issler-Fisher (2020)	Australia	No funding	78	Adult	Burn	3
Katz (1985)	United States	Not reported	4	Not reported	Burn	3
Kemp Bohan (2021)	United States	No funding	21	Not reported	Burn	3
Kim (2018)	Not specified	Not reported	148	Not reported	Burn	3
Li (2018)	China	Non-commercial	34	Adult	Burn	3
Li-Tsang (2005)	China	Non-commercial	101	Adult	Surgical (orthopaedic surgery)	3
Lobos (2017)	Not specified	Not reported	35	Paediatric & adult	Not specified	3
Nedelec (2008)	Canada	Non-commercial	32	Adult	Burn	3
Nedelec (2014)	Not specified	Non-commercial	46	Adult	Burn	3
Reinholz (2016)	Not specified	Commercial	8	Adult	Not specified	3
Simons (2017)	Australia	Non-commercial	49	Paediatric	Burn	3
Soykan (2014)	The Netherlands	Non-commercial	87	Adult	Surgical (cardiothoracic surgery)	3
Timar-Banu (2011)	Canada	Non-commercial	30	Adult	Mixed	3
Ud-Din (2019)	United Kingdom	Non-commercial	62	Adult	Not specified	3
van den Kerckhove (2003)	Not specified	Not reported	6	Adult	Burn	3

Wang (2010)	Australia	Commercial & Non-commercial	21	Paediatric	Burn	3
Wood (1996)	Not specified	Not reported	1	Paediatric	Burn	3
Yeol Lee (2022)	Korea	Non-commercial	16	Adult	Mixed	3
Berry (1985)	Not specified	Commercial	16	Paediatric & adult	Burn	4
Engrav (2010)	Not specified	Commercial & Non-commercial	67	Paediatric & adult	Burn	4
Abstracts						
Agabalyan (2016)	Not specified	Non-commercial	10	Not reported	Burn	2
Bajouri (2018)	Not specified	Not reported	20	Not reported	Burn	2
Blome-Eberwein (2011, 2012)	Not specified	Not reported	16	Paediatric & adult	Mixed	2
Blome-Eberwein (2014)	Not specified	Not reported	66	Not reported	Burn	2
Cho (2012)	Not specified	Not reported	60	Paediatric & adult	Burn	2
Comstock (2018)	Not specified	Not reported	1	Adult	Burn	2
Cooper (2021)	Not specified	Not reported	25	Not reported	Burn	2
El-Zawhary (2007)	Not specified	Not reported	57	Not reported	Mixed	2
Jacobs (2016)	Not specified	Not reported	6	Paediatric & adult	Burn	2
Jang (2009)	Not specified	Not reported	20	Not reported	Not specified	2
Kim (2009)	Not specified	Not reported	5	Paediatric & adult	Burn	2
Li-Tsang (2010)	Not specified	Not reported	45	Not reported	Not specified	2
Li-Tsang (2011)	Not specified	Not reported	4	Not reported	Not specified	2
Maari (2017)	Not specified	Non-commercial	12	Not reported	Not specified	2
Moortgat (2020)	Not specified	Not reported	10	Not reported	Burn	2
Nedelec (2018)	Not specified	Not reported	60	Not reported	Burn	2
Peters (2018)	Not specified	Not reported	5	Not reported	Burn	2
Siwy (2016)	Not specified	Non-commercial	15	Not reported	Burn	2
Tu (2014)	Not specified	Not reported	59	Not reported	Not specified	2
Ud-Din (2017)	Not specified	Not reported	20	Not reported	Surgical (tissue biopsies)	2
Anthonissen (2015)	Not specified	Not reported	N.R.	Not reported	Burn	3
Bezugly (2014)	Not specified	Not reported	103	Not reported	Mixed	3

Bezugly (2019)	Not specified	Not reported	438	Not reported	Not specified	3
Blome-Eberwein (2012)	Not specified	Not reported	19	Adult	Burn	3
Du (2006)	Not specified	Not reported	1	Adult	Burn	3
Edgear-Lacoursière (2022)	Canada	Not reported	44	Not reported	Burn	3
George (2019)	Not specified	Not reported	11	Not reported	Burn	3
Li (2016)	Not specified	Not reported	34	Not reported	Burn	3
Seo (2011)	Korea	Not reported	48	Not reported	Burn	3
Timina (2013)	Not specified	Not reported	49	Paediatric & adult	Not specified	3
Ud-Din (2017)	Not specified	Not reported	20	Not reported	Surgical (tissue biopsies)	3
Ud-Din (2018)	Not specified	Not reported	62	Not reported	Surgical (tissue biopsies)	3
Zuccaro (2019)	Canada	Not reported	13	Paediatric	Burn	3
Zuccaro (2021)	Not specified	Not reported	20	Paediatric	Burn	3
Zuccaro (2021)	Canada	Non-commercial	20	Paediatric	Burn	3
Cho (2012)	Not specified	Not reported	30	Not reported	Burn	4

Legend: Paediatric: measurement of patients under the age of 18; Adult: measurement of patients aged 18 years or older; N.R.: Not reported; Burn: scars caused by thermal, chemical or friction injury; Surgical: scars caused by surgical procedures (including biopsies); Mixed: participant scars caused by mixed trauma (e.g., burn and acne)

Footnotes: *Stage in the research to clinical practice translational pipeline, based on the Australian Government Department of Health and Aged Care[4]

Supplementary Table 3. Measurement methods used in included records.

First Author (year)	Ultrasound Type	Ultrasound Frequency (MHz)	Measurement Parameters	Scar Characteristic Measured	Scar Relocation
Journal articles					
Agabalyan (2017)	High-frequency	20	Epidermal, dermal & combined	N.R.	Not relevant – single measurement
Alsharnoubi (2018)	Midrange ultrasound	N.R.	N.R.	Fibrosis	N.R.
Alsharnoubi (2018)	Midrange ultrasound	N.R.	N.R.	Fibrosis†	N.R.
Alshehari (2015)	N.R.	N.R.	Maximum elevation above normal skin	N.R.	N.R.
Avetikov (2018)	B-mode	N.R.	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Berry (1985)	N.R.	N.R.	N.R.	N.R.	N.R.‡
Blome-Eberwein (2012)	B-mode	N.R.	Combined epidermal & dermal§	N.R.	N.R.‡
Blome-Eberwein (2016)	High-frequency	50	N.R.	Fibrosis†	N.R.‡
Blome-Eberwein (2019)	High-frequency	35	Dermal	Fibrosis, hair follicle density	N.R.
Cai (2019)	High-frequency	50	Dermal	N.R.	N.R.‡
Candy (2010)	B-mode	N.R.	N.R.	N.R.	Scar boundaries traced
Chae (2016)	N.R.	N.R	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Chang (2014)	N.R.	12	N.R.	N.R.	N.R.

Chan (2004)	N.R.	N.R.	N.R.	N.R.	Tracing
Cheng (2001)	B-mode	5-10	Combined epidermal & dermal	N.R.	Tracing & cutting out paper Photographs
Cho (2014)	High-frequency	7.5	N.R.	N.R.	N.R.
Danin (2012)	B-mode	20	Epidermal & dermal	N.R.	N.R.
Deng (2019)	N.R.	N.R.	N.R.	N.R.	N.R.
Deng (2021)	Colour Doppler	4-15	Dermal	Fibrosis[†]	N.R.
Deng (2021)	B-mode	8-12	Epidermal & dermal	Fibrosis[†]	Photographs
Dunkin (2007)	High-frequency	N.R.	N.R.	Fibrosis & oedema[†]	Measurements taken at set linear distances along scar
Elrefaie (2020)	High-frequency	13	N.R.	Fibrosis & oedema[†]	N.R[‡]
Engrav (2010)	N.R.	N.R.	N.R.	N.R.	N.R.
Fabbrocini (2016)	N.R.	N.R.	N.R.	Fibrosis & oedema[†]	N.R[‡]
Fong (1997)	B-mode	7.5	N.R.	Fibrosis[†]	Tracing
Fraccalvieri (2013)	High-frequency	7-10 & 10-13	N.R.	Fibrosis & oedema[†]	N.R.
Fraccalvieri (2011)	High-frequency	10-13	Combined epidermal & dermal	Fibrosis[†]	N.R.
Gankande (2014)	High-frequency	20	Combined epidermal & dermal	N.R.	Scar marked & photographed
Ge (2022)	N.R.	N.R.	N.R.	N.R.	N.R.
Gee Kee (2016)	B-mode	8-18	Combined epidermal & dermal	N.R.	Transducer in centre of original burn site where no scar present
Guo (2020)	N.R.	2-15 & 4-15	Combined epidermal & dermal[c]	Fibrosis[†]	Thickest site on peripheral regions
Huang (2017)	N.R.	N.R.	Combined epidermal & dermal	N.R.	Marked & linear measurements from bony landmarks

Huang (2021)	B-mode	5-12	N.R.	Oedema[†]	Not relevant – single measurement
Huang (2020)	B-mode	5-12	Combined epidermal & dermal	N.R.	N.R.
Issler-Fisher (2021)	N.R.	N.R.	N.R.	N.R.	Photograph & measurement of thickest area
Issler-Fisher (2020)	N.R.	N.R.	N.R.	N.R.	N.R.
Issler-Fisher (2017)	N.R.	N.R.	N.R.	Fibrosis[†]	Scar mapped with drawing Thickest area measured
Joo (2020)	N.R.	N.R.	N.R.	Fibrosis[†]	N.R.
Katz (1985)	B-mode	10	Combined epidermal & dermal	N.R.	N.R.
Kemp Bohan (2021)	High-frequency	12	N.R.	Fibrosis[†]	Tracing – thickest area & adjacent landmarks marked
Kim (2018)	N.R.	22	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Lacarrubba (2008)	B-mode	20	Combined epidermal & dermal	N.R.	N.R.
Lau (2005)	Tissue Ultrasound Palpation System	5 (burn) & 10 (surgical)	N.R.	N.R.	Tracing – most severe/prominent site
Lee (2020)	High-frequency	20	Combined epidermal & dermal	Fibrosis[†]	Not relevant – single measurement
Lee (2019)	High-frequency	20	Combined epidermal & dermal	Fibrosis[†]	Marked with pen
Li (2013)	High-frequency	12	Combined epidermal & dermal	Fibrosis[†]	Tracing
Li (2020)	N.R.	10	N.R.	Fibrosis[†]	N.R.
Li (2021)	High-frequency	20	N.R.	N.R.	Thickest area
Li (2021)	High-frequency	20	N.R.[§]	Fibrosis[†]	Thickest area
Li (2018)	N.R.	N.R.	Combined epidermal & dermal	N.R.	N.R.
Li-Tsang (2005)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2006)	B-mode	N.R.	N.R.	N.R.	N.R[‡]

Li-Tsang (2010)	B-mode	N.R.	N.R.	Fibrosis†	N.R.
Lobos (2017)	B-mode & colour Doppler	18	N.R.	Fibrosis†	Not relevant – single measurement
Mamdouh (2021)	High-frequency	N.R.	Combined epidermal & dermal§	Fibrosis†	N.R.
Meirte (2016)	High-frequency	22	Dermal	Fibrosis & oedema†	Marked with surgical pen, including boundaries of probe. Photograph of body position & probe location
Miletta (2021)	N.R.	50	N.R.	Fibrosis†	Tracing – worst scar
Nedelec (2014)	High-frequency	20	Combined epidermal & dermal	N.R.	Tracing including notable landmarks. Measurement site circled. Photograph
Nedelec (2008)	High-frequency	20	Combined epidermal & dermal	N.R.	Tracing including notable landmarks. Measurement site circled. Photograph
Nedelec (2019)	High-frequency	20	Combined epidermal & dermal	Fibrosis & oedema†	Tracing. Hole cut over measurement area
Nedelec (2020)	High-frequency	20	Combined epidermal & dermal	N.R.	Photograph
Nicoletti (2015)	N.R.	22	Epidermis to fascia	N.R.	N.R.
Niessen (1998)	B-mode	N.R.	N.R.	Fibrosis & oedema†	3cm border marked with tape – measurements lateral
Reinholz (2020)	B-mode	11	Combined epidermal & dermal	Fibrosis & oedema†	N.R.
Reinholz (2016)	B-mode	11	Combined epidermal & dermal§	Fibrosis & oedema†	N.R.
Schwaiger (2018)	B-mode	11	N.R.	Fibrosis & oedema†	N.R.
Simons (2017)	B-mode	8-18	Combined epidermal & dermal	N.R.	Tracing – scar & anatomical landmarks

Soykan (2014)	N.R.	3-9	N.R.	Fibrosis†	N.R.
Timar-Banu (2001)	High-frequency	20	Combined epidermal & dermal	Fibrosis†	N.R.
Ud-Din (2019)	High-frequency	50	Combined epidermal & dermal	Fibrosis	Defined anatomical location
van den Kerckhove (2003)	High-frequency	20	Combined epidermal & dermal	N.R.	Test sites marked. Thermoplastic splints created with space for transducer
van den Kerckhove (2005)	High-frequency	20	Combined epidermal & dermal	N.R.	Test site boundaries marked & traced
van der Veer (2010)	N.R.	7.5	N.R.	Fibrosis†	Standardised linear measurement points
Wang (2009)	High-frequency	N.R.	N.R.	Fibrosis†	N.R.
Wang (2010)	B-mode	N.R.	Combined epidermal & dermal	N.R.	Tracing – scar & anatomical landmarks
Wiseman (2020, 2021)	B-mode	N.R.	Combined epidermal & dermal	Fibrosis†	Centrally site of interest
Wood (1996)	B-mode	7 & 10	N.R.	N.R.	Transducer affixed to tracking arm
Xuan (2021)	High-frequency	20	N.R.	Fibrosis†	N.R.
Yeol Lee (2022)	B-mode	7-16	N.R.	N.R.	N.R.
Yim (2010)	High-frequency	12	N.R.	N.R.	N.R.
Zadkowski (2016)	B-mode	N.R.	Combined epidermal & dermal	N.R.	N.R.
Abstracts					
Agabalyan (2016)	N.R.	20	Epidermal, dermal & combined	N.R.	N.R.
Anthonissen (2015)	N.R.	22	Epidermal & dermal	N.R.	N.R.
Bajouri (2018)	High-frequency	N.R.	Epidermal & dermal	N.R.	N.R.

Bezugly (2019)	High-frequency	22, 33 & 75	Epidermal & dermal	N.R.	N.R.
Bezugly (2014)	High-frequency	33 & 75	Epidermal & dermal	N.R.	N.R.
Blome-Eberwein (2011, 2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Blome-Eberwein (2012)	High-frequency	N.R.	N.R.	Fibrosis	N.R.
Blome-Eberwein (2014)	High-frequency	N.R.	N.R.	N.R.	N.R.
Cho (2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Cho (2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Comstock (2018)	N.R.	N.R.	N.R.	N.R.	N.R.
Cooper (2021)	N.R.	N.R.	N.R.	N.R.	N.R.
Du (2006)	B-mode	15	N.R.	N.R.	N.R.
Edgar-Lacoursière (2022)	N.R.	N.R.	N.R.	N.R.	N.R.
El-Zawhary (2007)	N.R.	N.R.	N.R.	N.R.	N.R.
George (2019)	N.R.	N.R.	N.R.	N.R.	N.R.
Jacobs (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Jang (2009)	N.R.	N.R.	N.R.	N.R.	N.R.
Kim (2009)	N.R.	N.R.	N.R.	N.R.	N.R.
Li (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2011)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2010)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Maari (2017)	N.R.	N.R.	N.R.	N.R.	N.R.

Moortgat (2020)	High-frequency	N.R.	Dermal	N.R.	N.R.
Nedelec (2018)	N.R.	N.R.	N.R.	N.R.	N.R.
Peters (2018)	High-frequency	22	N.R.	N.R.	N.R.
Seo (2011)	N.R.	7.5	N.R.	N.R.	Thickest point
Siwy (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Timina (2013)	N.R.	20-40	N.R.	N.R.	N.R.
Tu (2014)	High-frequency ultrasound biomicroscopy	N.R.	N.R.	N.R.	N.R.
Ud-Din (2017)	N.R.	N.R.	N.R.	N.R.	N.R.
Ud-Din (2017)	High-frequency	50	N.R.	N.R.	N.R.
Ud-Din (2018)	High-frequency	N.R.	N.R.	Fibrosis[†]	N.R.
Zuccaro (2021)	N.R.	N.R.	N.R.	N.R.	N.R.
Zuccaro (2019)	B-mode	N.R.	N.R.	N.R.	N.R.
Zuccaro (2021)	B-mode	6-18	Combined epidermal & dermal	N.R.	Scar outlined & photographed

Legend: Scar relocation: Methods used by assessors to relocate the measured scar for sequential measurements; B-mode: brightness-mode ultrasound (< 20 MHz); High-frequency: high-frequency B-mode ultrasound (> 20 MHz); N.R.: Not reported

Footnotes: [†]Indirect reference made in record (e.g. in introduction or discussion); [‡]Photographs taken of the scar but not specified whether used for relocation; [§]Not stated in methods, so images provided in record used by authors of this review to provide subjective judgement

Supplementary Table 4. Additional measurement methods used alongside ultrasound in included studies

First author (year)	**Objective measurement methods**	**Clinician-based rating scale**	**PROM**
Journal articles			
Agabalyan (2017)	Histology	-	-
Alsharnoubi (2018)	Laser Doppler perfusion	VSS	-
Alsharnoubi (2018)	Laser Doppler perfusion	VSS	-
Alshehari (2015)	-	VSS	-
Avetikov (2018)	-	-	-
Berry (1985)	Transcutaneous oxygen measurement	Scar redness and hypertrophy rating scale (0-5 Likert scale)	Scar redness and hypertrophy rating scale (0-5 Likert scale)
Blome-Eberwein (2012)	Doppler flowmeter – vascularity Cutometer – pliability Semmes-Weinstein monofilament Aesthesiometer testing set – sensation	VSS POSAS-O	POSAS-P
Blome-Eberwein (2016)	Cutometer – pliability Dermaspectrometer – colour Semmes-Weinstein Aesthesiometer Monofilament Testing Set – sensation	VSS POSAS-O	POSAS-P
Blome-Eberwein (2019)	-	VSS	-
Cai (2019)	-	Clinical evaluation	-
Candy (2010)	Spectrocolorimeter – colour	VSS	-
Chae (2016)	Spectrophotometer – pigmentation	VSS POSAS-O	POSAS-P
Chang (2014)	-	VSS Photographic evaluation (0-10 VAS)	-
Chan (2004)	Cutometer – viscoelasticity Spectrophotometer – pigmentation	-	-
Cheng (2001)	-	VSS	-
Cho (2014)	Mexameter – colour	Treatment efficacy (0-10 VAS)	Itching scale (0-4 Likert scale)

	Tewameter – trans-epidermal water loss Sebumeter – sebum Cutometer – elasticity		
Danin (2012)	Cutometer – elasticity	VSS	-
Deng (2019)	DermaLab Combo – colour Dermoscopy – vascularity	POSAS-O	-
Deng (2021)	-	VSS	-
Deng (2021)	Doppler – blood perfusion Dermlite Foto IIPro – erythema	POSAS-O	POSAS-P
Dunkin (2007)	-	-	-
Elrefaie (2020)	Ultrasound – echogenicity, compressibility & vascularity	VSS	-
Engrav (2010)	Durometer – hardness Chromameter – colour	Clinical appearance based on photographs	-
Fabbrocini (2016)	-	mVSS (vascularity, pigmentation, pliability)	-
Fong (1997)	Cutometer – elasticity	Clinical rating – colour change, consistent itch, hypersensitivity, blistering	-
Fraccalvieri (2013)	Colour power Doppler – vascularisation	VSS Visual analogue scale – pain and itch	
Fraccalvieri (2011)	Histology Echocontrastography – neovascularisation	-	-
Gankande (2014)	DermLab combo – erythema & elasticity	mVSS (some participants)	-
Ge (2022)	-	POSAS-O Subjective reports on patient range of movement	POSAS-P
Gee Kee (2016)	3D photography – thickness	POSAS-O	POSAS-P
Guo (2020)	Ultrasound – blood flow grade Shear wave elastography – scar stiffness	-	-

Huang (2017)	-	-	-
Huang (2021)	-	-	-
Huang (2020)	Shear wave elastography – scar stiffness	-	-
Issler-Fisher (2021)	-	VSS POSAS-O	POSAS-P
Issler-Fisher (2020)	-	VSS POSAS-O	POSAS-P Patient pain & itch scales
Issler-Fisher (2017)	-	VSS POSAS-O	POSAS-P Patient pain, itch & quality of life rating scales
Joo (2020)	-	VSS	Pain severity (0-10 VAS)
Katz (1985)	Cicatrometer – firmness	-	-
Kemp Bohan (2021)	-	-	-
Kim (2018)	-	-	-
Lacarrubba (2008)	-	Clinical evaluation of lesion size	-
Lau (2005)	-	VSS	-
Lee (2020)	-	mVSS (height, pliability, vascularity, pigmentation) POSAS-O	POSAS-P
Lee (2019)	-	mVSS (height, pliability, vascularity, pigmentation) POSAS-O	POSAS-P
Li (2013)	Micrometer – tissue thickness Force/torque sensor – load applied to scar	-	-
Li (2020)	Cutometer – elasticity Mexameter – colour PeriCam PSI system and mexameter – blood supply	VSS	Quality of life questionnaire
Li (2021)	Laser Doppler flowmetry – perfusion	VSS	-
Li (2018)	Spectrocolourimeter – scar colour	VSS	Pain & itch (0-10 VAS)
Li (2021)	-	VSS	Treatment satisfaction
Li-Tsang (2005)	Spectrocolourimeter – scar colour	VSS	Pain & itch (VAS scale not specified)
Li-Tsang (2006)	Spectrocolorimeter – colour	VSS	Pain & itch (VAS)

Li-Tsang (2010)	Spectrocolorimeter – colour	VSS (pliability)	Pain & itch (10-point VAS)
Lobos (2017)	-	Modified Seattle Scar Scale Clinical opinion	-
Mamdouh (2021)	-	VSS	Patient satisfaction (VAS)
Meirte (2016)	-	-	-
Miletta (2021)	Colourmeter – scar colour Dermal torque meter – scar compliance	Unclear, likely POSAS-O	Unclear, likely POSAS-P Short Form 36 Quality of Life Survey
Nedelec (2014)	Cutometer – elasticity Mexameter – colour	-	-
Nedelec (2008)	Cutometer – elasticity Mexameter – colour	mVSS	-
Nedelec (2019)	Cutometer – elasticity Mexameter – colour	-	-
Nedelec (2020)	Cutometer – elasticity Mexameter – colour	-	Pain & itch (10cm line VAS)
Nicoletti (2015)	-	-	-
Niessen (1998)	Histology	-	-
Reinholz (2020)	3D topographic imaging device	POSAS-O	Dermatology Quality of Life Index POSAS-P
Reinholz (2016)	Optical coherence tomography – thickness	POSAS-O	Dermatology Quality of Life Index POSAS-P
Schwaiger (2018)	3D topographic imaging device	-	-
Simons (2017)	3D camera – scar height	POSAS-O	-
Soykan (2014)	Slide calliper – dimensions	POSAS-O	POSAS-P
Timar-Banu (2001)	Metric ruler – dimensions	Validated 3-point scoring system for redness, hardness, itching & pain	-
Ud-Din (2019)	Optical coherence tomography – thickness Histology	-	-
van den Kerckhove (2005)	Chromameter – erythema	-	-
van der Veer (2010)	Slide calliper – dimensions	-	-
Wang (2009)	Histology	-	-
Wang (2010)	-	-	-

Wiseman (2020, 2021)	-	POSAS-O	POSAS-P Numeric rating scale for itch Toronto Paediatric Itch Scale CH-9D BBSIP
Wood (1996)	-	VSS	-
Xuan (2021)	Histology	-	-
Yeol Lee (2022)	Cutometer – elasticity Elastography	mVSS	-
Yim (2010)	Cutometer – elasticity Tewameter – trans-epidermal water loss Mexameter – colour	-	-
Zadkowski (2016)	-	VSS	-
Abstracts			
Agabalyan (2016)	Histology	-	-
Bajouri (2018)	-	VSS	-
Bezugly (2019)	Clinical or histopathological diagnosis	-	-
Bezugly (2014)	-	-	-
Blome-Eberwein (2011, 2012)	Doppler vascularity, elasticity and sensation	VSS	Pain and itching scale (0-10 Likert scale)
Blome-Eberwein (2012)	-	-	-
Blome-Eberwein (2014)	Doppler flowmeter – vascularity Cutometer – pliability Semmes-Weinstein monofilament aesthesiometer testing set – sensation	VSS	POSAS-P
Cho (2012)	-	VSS	-
Cho (2012)	CK-MPA Multi-Probe adaptor – pigmentation, erythema and trans-epidermal water loss Cutometer – elasticity	-	-
Comstock (2018)	Computer-based tools – Thickness & pliability	Unclear, likely POSAS-O	Unclear, likely POSAS-P

Cooper (2021)	Colorimeter – pigmentation	Unclear, likely POSAS-O	Unclear, likely POSAS-P
Du (2006)	-	-	-
Edgar-Lacoursière (2022)	Cutometer – elasticity Mexameter – colour	-	-
El-Zawhary (2007)	Histology	-	-
George (2019)	-	-	-
Jacobs (2016)	Cutometer – pliability Colorimeter – colour	POSAS-O	-
Jang (2009)	Mexameter – pigmentation Tewameter – trans-epidermal water loss Sebumeter – sebum Cutometer – elasticity Laser Doppler – perfusion	-	-
Kim (2009)	Histology	VSS	-
Li (2016)	Spectrocolourimeter – scar colour	VSS	Patient report of pain & itch
Li-Tsang (2011)	-	VSS (thickness, pliability and pigmentation)	-
Li-Tsang (2010)	Histology Spectrocolourimeter – scar colour	VSS	Self-report questionnaire
Maari (2017)	Cutometer – elasticity Mexameter – pigmentation	-	-
Moortgat (2020)	Cutometer – elasticity Chromameter – colour Tewameter – trans-epidermal water loss Corneometer – hydration	Unclear, likely POSAS-O	Unclear, likely POSAS-P
Nedelec (2018)	Cutometer – elasticity Mexameter – colour	-	-
Peters (2018)	Cutometer – elasticity Colourimeter – colour	POSAS-O	POSAS-P
Seo 2011	Cutometer – elasticity		
Siwy (2016)	Colourimeter – colour Torque meter – pliability & elasticity	-	SF-36 Quality of Life Measurement POSAS-P
Timina (2013)	-	-	-

Tu (2014)	-	VSS	-
Ud-Din (2017)	Laser perfusion imaging Optical coherence tomography – thickness Histology	-	-
Ud-Din (2017)	Optical coherence tomography – thickness	-	-
Ud-Din (2018)	Optical coherence tomography – thickness Histology	-	-
Zuccaro (2021)	Multi-parameter skin analysis device	VSS Unclear, likely POSAS-O	Unclear, likely POSAS-P
Zuccaro (2019)	Acoustic radiation force impulse ultrasound elastography	-	-
Zuccaro (2021)	Acoustic radiation force impulse – stiffness DermLab Combo elasticity probe – elasticity DermLab Combo colour probe – colour	VSS POSAS-O (did not include surface area and relief subscales)	POSAS-P

Legend: (m)VSS: (Modified) Vancouver Scar Scale; POSAS: Patient and Observer Scar Assessment Scale (POSAS-O: POSAS observer scale; POSAS-P: POSAS patient scale); VAS: Visual Analogue Scale; CHU-9D: Child Health Utility-9D; BBSIP: Brisbane Burn Scar Impact Profile

Supplementary Table 5: Reliability of ultrasound methods reported in each included study

First Author (year)	Reliability Test & Measurement Error	Reliability & Measurement Error Test Statistics & Details
Inter-rater reliability		
Anthonissen (2015)	ICC; SEM	Epidermal – 0.297; 0.02mm Dermal – 0.991; 0.13mm
Chang (2014)	Pearson correlation	R=0.90, p<0.001
Dunkin (2007)	N.R.	N.R.
Fong (1997)	ICC	0.93, p=0.146
Gankande (2014)	ICC (95% CI)	Individual site: **Rater 1 vs rater 2** 'Best scar' – 0.95 (0.92, 0.96) 'Worst scar' – 0.95 (0.91, 0.97) 'Normal skin' – 0.94 (0.91, 0.96) **Rater 1 vs rater 3:** 'Best scar' – 0.86 (0.78, 0.91) 'Worst scar' – 0.91 (0.85, 0.95) 'Normal skin' – 0.92 (0.88, 0.95) **Rater 2 vs rater 3:** 'Best scar' – 0.93 (0.89, 0.95) 'Worst scar' – 0.96 (0.92, 0.97) 'Normal skin' – 0.95 (0.92, 0.97) Average site: **Rater 1 vs rater 2** 'Best scar' – 0.97 (0.94, 0.99) 'Worst scar' – 0.98 (0.96, 0.99) 'Normal skin' – 0.97 (0.93, 0.98) **Rater 1 vs rater 3** 'Best scar' – 0.90 (0.77, 0.95) 'Worst scar' – 0.97 (0.91, 0.98) 'Normal skin' – 0.96 (0.92, 0.98) **Rater 2 vs rater 2** 'Best scar' – 0.95 (0.88, 0.98) 'Worst scar' – 0.98 (0.94, 0.99) 'Normal skin' – 0.98 (0.97, 0.99)
Lau (2005)	ICC	0.84, p<0.01
Lee (2020)	ICC	"Acceptable to high"
Lee (2019)	ICC (95% CI); SEM	Scar: Single: 0.957 (0.934-0.973) Average: 0.985 (0.977-0.991) SEM: 0.10 mm Unscarred skin: Single: 0.967 (0.949-0.980) Average: 0.989 (0.982-0.993) SEM: 0.04 mm
Nedelec (2008)	ICC (95% CI)	Most severe scar: 0.90 (0.84-0.95) Less severe scar: 0.91 (0.85-0.95) Donor site: 0.89 (0.82-0.94) Normal skin: 0.85 (0.75-0.92)
Seo (2011)	N.R.	"High"
Simons (2017)	ICC (95% CI); SEM	Scar: 0.82 (0.7-0.89); 0.05 cm Normal skin: 0.33 (0.08-0.54); 0.03 cm
Van Den Kerckhove (2003)	ICC (95% CI); SEM	One day: 0.88 (0.81-0.95); 0.29 mm

		Day-to-day: 0.94 (0.90-0.98); 0.21mm
Intra-rater reliability		
Anthonissen (2015)	ICC; SEM	Epidermal – 0.809; 0.01mm Dermal – 0.991; 0.13mm
Gankande (2014)	ICC (95% CI)	'Best scar' – 0.97 (0.89, 0.94) 'Worst scar' – 0.92 (0.88, 0.95) 'Normal skin' – 0.86 (0.81, 0.89)
Gee Kee (2016)	N.R.	N.R.
Lau (2005)	ICC	Intra-rater: 0.98, p<0.01
Lee (2019)	ICC (95% CI)	Scar: Single: 0.951 (0.871-0.987) Average: 0.983 (0.953-0.966) SEM: 0.10 mm Unscarred skin: Single: 0.948 (0.881-0.976) Average: 0.982 (0.954-0.993) SEM: 0.04 mm
Li (2013)	ICC	0.89
Seo (2011)	N.R.	"High"
Simons (2017)	ICC (95% CI); SEM	Scar: 0.95 (0.91-0.97); 0.02 cm Normal skin: 0.61 (0.41-0.75); 0.02 cm
Van Den Kerckhove (2003)	ICC (95% CI); SEM	0.98 (0.97-0.99); 0.11mm
Wang (2010)	SE	Peak: 0.032 3 months: 0.018 6 months: 0.399 9 months: 0.353

Abbreviations used in tables: N.R.: Not reported; ICC: Intraclass Correlation Coefficient; 95% CI: 95% Confidence Interval; SEM: Standard Error of Measurement; SE: Standard Error

Summary of findings for measurement error:

The reported inter-rater SEM measurements for the combined (i.e., epidermal and dermal) thickness measurement of scars was reported in two records as 0.11 mm[5] and 0.5 mm.[6] The inter-rater SEM for the combined thickness measurement of unscarred skin was also calculated in one record (SEM = 0.3 mm).[6] The inter-rater SEM was calculated in one record for the measurement of epidermal (SEM = 0.02 mm) and dermal (0.13) measurements[7], and one record reported only the dermal SEM for scar thickness (SEM = 0.1 mm) and unscarred skin (0.04 mm).[8] The intra-rater SEM for the combined thickness measurement of scarred skin ranged from 0.18 mm to 0.52 mm, and was measured at 0.2 mm for unscarred skin in one record.[6] One record reported the intra-rater SEM for epidermal (0.01 mm) and dermal (0.12 mm),[7] and one record reported the intra-rater SEM for dermal scar (0.1 mm) and unscarred skin (0.04).[8]

Supplementary Table 6. Methodological considerations for researchers and/or clinicians undertaking measurement of scar thickness using ultrasound.

Consideration	Details & examples of considerations	Publications in our review addressing the consideration	Details reported in included review records
Preventing skin compression during measurement	Using standoff methods (e.g., ultrasound gel, water bath) to prevent transducer touching the skin	6,9-13	- Use of ultrasound gel to prevent contact between ultrasound transducer and skin surface to minimise compression applied by direct application of transducer [6,9-12] - Silicone pad placed underneath transducer [13]
	Application of minimal pressure by transducer	14-18	- Transducer held to maintain minimal pressure on scar [14,15,17] - Training users to apply minimal force on transducer to prevent scar or skin distortion [16,18]
	Deliberately compressing skin to quantify scar compressibility	19-21	- Measurement of thickness with and without compression with transducer [19,21] - Thickness measurements taken using TUPS, which uses controlled and metered compression during measurement [20]
Orienting the patient	Orienting the patient during measurement (e.g., upright, supine, prone or seated)	8,18,22	- Patient supine throughout measurement to allow measurement to be taken in the same position [8,18,22]
	Maintaining patient stillness during measurement	9	- Patients asked to hold breath during measurement of scars on the chest to allow shear-wave ultrasound [9]
Placing ultrasound transducer	Orientating ultrasound transducer [e.g., vertical (superior to inferior/cranial to caudal), horizonal (medial to lateral)]	23	- Direction of transducer recorded to ensure consistency [23]

	Orienting the transducer in relation to the scar (e.g., perpendicular)	9,15,17,18,22,24-26	- Transducer oriented perpendicular to the skin surface to provide optimal image [9,15,18,22,24-26]
	Measuring difficult/tight areas (e.g., axillae or other joints)	6	- Exclusion of fingers and toes in paediatric measurements due to size of measurement area and thin skin [6]
Relocating scars for longitudinal measurement	Mapping measurement area (e.g., tracing, schematic diagram)	6,12,16,18,20,22,27-32	- Scars traced using translucent paper [18,20,22,27,29,31,32] - Scars and surrounding anatomical landmarks traced using translucent paper [16] - Scar mapped on transparent paper, which was then cut out [28] - Scar mapped with drawing, no elaboration provided [30] - Scars traced using Visitrak (Smith & Nephew Medical Limited, England) [6,12]
	Photographing measurement area	24,26,33	- Assessed area marked and photograph taken in initial consultation [24,33] - Photographs of scars taken [26]
	Measuring specific scar locations (e.g., centre of scar, worst area of scar, counting transducer lengths)	6,8,9,13,19-21,23,30,33-37	- Measurement taken at standardised transducer lengths along surgically created scars of pre-specified dimensions [34] - Measurements taken at thickest/most severe point [19-21,30,33,35,37], as determined by the patient and/or clinician [8] - Transducer placed on thickest site on peripheral regions [9] - Transducer placed on area initially identified to have greatest burn depth [23]

			- Measurement area selected by the measurer with -selected area marked with tape [13] - Measurements taken at set linear distances from cranial/caudal border of linear sternal scar [36]
	Conducting linear measurements from nearby anatomical landmarks	17,38	- Linear measurements from anatomical landmark to measurement site [17] - Transducer placement mapped in 3-dimensional space using a surgical precision tracking arm [38]
Acclimatising scar to measurement conditions	Removing scar treatments prior to ultrasound measurement	8,12,20,22,24-26,28,29,39,40	- Pressure garments removed 10 minutes before measurement [28] - Pressure garments removed 15 minutes before measurement to regain original (uncompressed) scar thickness or to reduce blanching effects on measurement [20,40] - Pressure garments/gels/moisturisers removed 20 minutes before measurement [8,22,29] - Pressure garments removed 30 minutes before measurement [12,25,26,39] - Sequential measurement of scars following direct treatment with vacuum massage at 5, 30, 60 and 120 minutes to monitor effect of treatment [24]
	Acclimatising patient to room prior to measurement	5,18,22,29,41-46	- Patients rested for minimum 5 minutes before measurement [5,18,22] - Scar exposed to room conditions for 10 minutes [29] to allow equilibrium to be reached with surrounding environment [41] - Patients resting in room with constant temperature for 15 mins [42] to allow scar to stabilise [44]

			- Patients rested for 20 minutes prior to measurement [29,45] - Patients resting for 10 minutes before repeated measurements taken [43] - Patients wait in testing room holding position for 5 min before measurement to stabilise cutaneous blood flow [5] - Patients allowed to adapt in controlled room to exclude external variables [46]
	Maintaining patient position before measurement	11,13	- Patients remained supine for at least 5 minutes before measurement to avoid artefacts on Doppler imaging [13] - Patients allowed to acclimatise to room and assumed a supine position for a minimum of 10 minutes before measurements of biophysical parameters [11]
Measuring different skin layers	Measuring epidermis and/or dermis individually	7,24,37,45,47-54	- Measurement of epidermal, dermal and combined epidermal and dermal thickness to allow comparison with histological measurement [47,48] - Measurement of the epidermal and dermal thickness [45,49], combined with layer acoustic density [7] - Measurement of the epidermal, dermal and subcutaneous thickness, combined with acoustic density [50,51] - Measurement of dermal thickness as treatment thought to affect/target the dermis [24,37,52-54]
	Measuring both epidermis/dermis combined (no	5,6,8,11,12,15,17,18,22,23,26,28,35,40,55-68	- Combined epidermal and dermal thickness measurement to provide information on the full thickness of the scar [5,6,8,11,12,15,17,18,22,23,26,28,35,40,55-68]

	individual measurement)		
Measurement objective	Measuring fibrosis/oedema/hair follicles	8,10,11,13,14,16,17,24,25,29-32,34,36,37,45,54,58,60,61,63,64,69-82	- Measurement of fibrosis or collagen architecture [8,11,17,24,29-32,34,36,37,45,54,58,61,63,64,69,70,72-74,77-79,82] - Measurement of inflammation/oedema [14] - Quantification of the sub epidermal low echogenic band, indicating oedema [60] - Measurement of both fibrosis and oedema [10,13,16,25,58,71,75,76,80,81] - Measurement of the presence and density of hair follicles to differentiate scarred and unscarred skin[54]
Factors influencing scar site measurement	Measuring contralateral skin/control scar	9,14,15,23,29,30,52,55-58,83-88 6,8,12,18,22,25,38,43,54,59-61,66,89,90 39,40,45,79,81,82	- Measurement of additional, non-scarred subjects [55,79] - Measurement of unscarred/unaffected skin on same subject as scar measurement contralaterally or at anatomically similar location to provide normative measurements for skin thickness [6,8,9,12,14,15,18,22,23,29,30,38-40,43,45,52,54,56-61,66,81,85-90] - Measurement of both untreated scar and unaffected skin [82-84] - Measurement of a control scar subjected to care as usual treatment on the same individual [25]
	Measuring open wounds or sores in the scar	6	- Use of flexible transparent plastic wrap placed over the measurement area to prevent contact between ultrasound gel and transducer with the open wound/sore [6]
	Operator training and/or experience	6,8,12,14,16,18,20,24,27-29,31,39,40,58,61,66,72,73,87,91-93	- Trained outcome assessor [6,13,16,18,27,72] - Measurements taken by radiologist/sonographer [28,66,73,92]

		- Assessors with burn experience [87,93] - Ultrasound located in department of radiology [91] - Measurements conducted by trained therapist/doctor under guidance of experienced radiologist [12,14,29,39] - Measurements conducted by trained clinicians who use device regularly and received training by company representative of devices [8,61] - Device-specific training provided: 1 week [20]; 3 sessions of 3 hours for 3 weeks, plus 10 independent assessments of scars using study protocol [40]; training provided over 3 months [31]; physical therapist trained in ultrasound application [24]
Number of measurements per scar	5,6,8,9,11,12,20,23,25,26,31,34,37,40,44,45,47,52,54,57,60,61,66,68,79,85,92,94	- 3 ultrasound images taken from each patient [9,11,26,31,37,44,45,47,52,54,57,60,79,85] - Clearest of 3 measurements used [12] - 3 measurements in 3 locations across scar used. Individual and average measurements reported [40] - Measurements performed in duplicate [34,94] - Measurements taken at different points of the scar, thickest used for analysis [92] - 5 measurements of each site [6,23] - 9 measurements taken, removal of maximum and minimum, 7 measurements used for average [20] - Measurements taken by 3 assessors at 3 different time points during day [8,61] - Measurement of 2 sites on the same scar [25] - Single ultrasound image taken for analysis [68]

Use of additional measurement tools as well as ultrasound measurements	Using additional objective assessment instruments (e.g., histology, colour Doppler ultrasound, cutometer, colourimeter)	6,9-11,13,15,17,18,21-23,25-27,29,31,32,35,36,40-48,50,53,56-59,66,68-70,75-80,82-84,86-92,95-111	- Histology/immunohistochemistry [13,17,47,48,50,58,78,79,88,100,103,108,110] - Blood flow and blood perfusion measurement using laser Doppler perfusion imaging, flowmetry or PeriCam, and scar colour and micro-vessel percentage using dermoscopyolour and micro-vessel percentage. [35,69,70,83,84,86,87,92,99,101,108] - Oximeter [41] - Infra-red camera [41] - Measurement of scar stiffness or pliability/elasticity using elastography or cutometer [9,15,18,21,22,25-27,29,43,46,53,57,66,82-84,86,89,90,96,98,99,101,104-106] - Measurement of sensation using Semmes-Weinstein filaments [82-84,86] - Measurement of scar colour (including pigmentation and erythema) using spectrophotometer, colourimeter, chromameter, mexameter or Dermlite Foto IIPro [18,22,25-27,32,42,44-46,53,56,66,68,80,82,87,90,91,96-99,101-107,111] - Measurement of trans-epidermal water loss using Tewameter or scar hydration using Corneometer [46,53,96,99] - Measurement of sebum level using sebumeter [96,99] - Measurement of hardness using durometer [91] - Measurement of neovascularisation using echocontrastography [58] - Measurement of scar dimensions (e.g., scar height and volume) using 3D camera, 3D imaging methods, ruler or calliper [6,10,11,23,36,75,77]

		- Measurement of skin thickness using micrometer or optical coherence tomography [17,31,59,76,108-110] - Measurement of scar firmness or deformation using cicatrometer, force/torque sensor (in line with ultrasound to measure load applied) or torque meter [31,32,107] - Multi-parameter skin analysis device [66] - Measurement of erythema and elasticity using probes of DermaLab Combo [40] - Multi-probe adaptor taking multiple measurements (pigmentation, erythema, trans-epidermal water loss) [96]
Using subjective assessment instruments (e.g., clinical rating scales, PROMs)	19,20,23,28-30,33,37,40,41,44,45,49,52,56,57,61,66,67,69-72,80-84,86,87,91,92,94-98,100,111-115	PROMs: - Measurement of scar quality using POSAS patient report [8,23,30,33,45,56,61,63,64,66,75-77,82,86,95,97,106,107,114,115] - Subjective rating scales for scar symptoms (e.g., pain, itch) or subjective scar severity ratings [26,30,41,42,53,63,64,72,80,83,84,93,102,103,111,115] - Patient quality of life questionnaires [75,76,101,107] - Measurement of generic health-related quality of life using CHU-9D [63,64] - Measurement of scar-specific health-related quality of life using BBSIP [63,64] - subjective evaluation of response to treatment/treatment satisfaction [81,116] Clinical rating scales: - Measurement of scar quality using POSAS observer report [8,23,30,33,45,53,56,61,63,64,66,75-77,82,86,87,97,98,106,114-116]

		- Measurement of physical scar characteristics using VSS or modified versions of the VSS [8,18-20,28,30,33,35,37,38,40,42-44,49,56,57,61,65,66,69-72,80-86,92-95,100-103,111-113,115,117,118] - Measurement of scar characteristics in relation to unscarred skin using Seattle Scar Scale or modified Seattle Scar Scale [73] - Subjective rating scales for scar symptoms (e.g., pain, itch) as assessed by the clinician and/or researcher and/or clinical evaluation of scar severity [11,29,41,52,57,67,73,91,92,94,96]
Determining the order of measurement	6	- Standardised order of measurement: 3D photograph, POSAS-O, then ultrasound [6] - Order of device use not specified [35,69,70,83,84,86,87,92,99,101,108]

Abbreviations: TUPS: Tissue Ultrasound Palpation System; 3D: three-dimensional; POSAS: Patient and Observer Scar Assessment Scale; CHU-9D: Child Health Utility 9D; BBSIP: Brisbane Burn Scar Impact Profile; VSS: Vancouver Scar Scale; mVSS: Modified Vancouver Scar Scale; POSAS-O: Patient and Observer Scar Assessment Scale, observer measure

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Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	3-4
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	5-7
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	7
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	7
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	8-10
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	8
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	9
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	9
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	10-11
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	10-11 and supplementary table 1
Critical appraisal of individual	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe	N/A

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
sources of evidence§		the methods used and how this information was used in any data synthesis (if appropriate).	
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	10-11
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	11-12
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	12-15
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Results section (11-46)
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Results section (11-46)
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	47-49
Limitations	20	Discuss the limitations of the scoping review process.	49-50
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	50-51
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	51

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

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Ultrasound measurement of traumatic scar and skin thickness: A scoping review of evidence across the translational pipeline of research-to-practice

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Ultrasound measurement of traumatic scar and skin thickness: A scoping review of evidence across the translational pipeline of research-to-practice*

Running Title: Review of scar thickness measurement with ultrasound

Brandon Meikle[1,2**], Megan Simons[2,3,7], Tamsin Mahoney[4], Tristan Reddan[5,6], Bryan Dai[2], Roy M Kimble[1,2,6,7] and Zephanie Tyack[2,8]

[1] Centre for Children's Burns and Trauma Research, Queensland Children's Hospital, Brisbane, Queensland, Australia

[2] Children's Health Research Centre, Faculty of Medicine, The University of Queensland, Herston, Queensland, Australia

[3] Occupational Therapy Department, Queensland Children's Hospital, Children's Health Queensland Hospital and Health Service, Brisbane, Queensland, Australia

[4] Surgical, Treatment and Rehabilitation Services (STARS), Metro North Hospital and Health Service, Brisbane, Queensland, Australia

[5] Medical Imaging and Nuclear Medicine, Queensland Children's Hospital and Health Service, Brisbane, Queensland, Australia

[6] School of Clinical Sciences, Faculty of Health, Queensland University of Technology, Brisbane, Queensland, Australia

[7] Pegg Leditschke Children's Burns Centre, Queensland Children's Hospital, Children's Health Queensland Hospital and Health Service, Brisbane, Queensland, Australia

[8] Australian Centre for Health Service Innovation (AusHI), Centre for Healthcare Transformation, and School of Public Health and Social Work, Queensland University of Technology, Brisbane, Queensland, Australia

** Corresponding author

E-mail: brandon.meikle@uq.net.au (BM)

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ABSTRACT:

Objectives: To identify the ultrasound methods used in the literature to measure traumatic scar thickness, and map gaps in the translation of these methods using evidence across the research-to-practice pipeline.

Design: Scoping review

Data Sources: Electronic database searches of Ovid MEDLINE, Embase, Cumulative Index of Nursing and Allied Health Literature (CINAHL) and Web of Science. Grey literature searches were conducted in Google. Searches were conducted from inception (date last searched 27/05/2022).

Data Extraction: Records using B-mode ultrasound to measure scar and skin thickness across the research-to-practice pipeline of evidence were included. Data was extracted from included records pertaining to: methods used; reliability and measurement error; clinical, health service, implementation and feasibility outcomes; factors influencing measurement methods; strengths and limitations; and use of measurement guidelines and/or frameworks.

Results: Of the 9309 records identified, 118 were analysed (n = 82 articles, n = 36 abstracts) encompassing 5213 participants. Reporting of methods used was poor. B-mode, including high-frequency (i.e., > 20 MHz) ultrasound was the most common type of ultrasound used (n = 72 records; 61% of records), and measurement of the combined epidermal and dermal thickness (n = 28; 24%) was more commonly measured than the epidermis or dermis alone (n = 7, 6%). Reliability of ultrasound measurement was poorly reported (n=14; 12%). The scar characteristics most commonly reported to be measured were epidermal oedema, dermal fibrosis and hair follicle density. Most records analysed (n = 115; 97%) pertained to the early stages of the research-to-practice pipeline, as part of research initiatives.

Conclusions: The lack of evaluation of measurement initiatives in routine clinical practice was identified as an evidence gap. Diverse methods used in the literature identified the need for greater standardisation of ultrasound thickness measurements. Findings have been used to develop nine methodological considerations for practitioners to guide methods and reporting.

STRENGTHS AND LIMITATIONS OF THIS STUDY:

- Use of the Australian Government Department of Health and Aged Care Medical Research Future Fund research-to-practice pipeline phases to categorise records allowed identification of gaps in the use of ultrasound for clinical practice.
- Clinical, health service, implementation and feasibility outcomes related to ultrasound measurement in included records were summarised to determine what is needed to close the research-to-practice gap for ultrasound measurement of scar thickness.
- A limitation is that only articles available in English or with an English abstract were considered for inclusion and data extraction, thus findings are likely most relevant to English speaking countries.

INTRODUCTION:

Traumatic cutaneous injury, caused by sharp object penetration (e.g., surgery or vaccination) or burns (including thermal, chemical and friction) may result in the formation of hypertrophic scarring. (1) Hypertrophic scars result from an aberrant cutaneous healing response that leads to the formation of red, raised scars, often accompanied by pruritus and skin tightening, which remain within the boundaries of the initial injury. (2-7) The sequelae of hypertrophic scars can impact on patient's physical and psychosocial quality of life. (8, 9)

A characteristic of hypertrophic scarring that both patients and clinicians have identified as being important, and which has subsequently been used as a way to measure clinical and treatment outcomes, is scar thickness. (9-17) Scar thickness can be measured both subjectively, through clinician assessment and patient-reported outcomes, or objectively, utilising medical imaging methods. (18, 19) The pathological complexity of hypertrophic scars means that they generally extend below the level of the surrounding skin, supporting the use of medical imaging modalities such as ultrasound for thickness quantification, as these are capable of providing information about subcutaneous structures and processes. (19, 20) Scar thickness measurement using ultrasound can be conducted in both clinical and research contexts. Where routine measurements like ultrasound are used to guide clinical decision-making and treatment, this practice is known as measurement-based care. (21)

Ultrasound is a safe, non-invasive and largely cost-effective (compared to other imaging modalities) imaging method with measurement utility in both adult and paediatric populations. (22-24) Modern B-mode (brightness mode) ultrasound, particularly high- (i.e., ≥20 MHz) or ultra-high frequency (30-100 MHz) (25) ultrasonography, allows differentiation between the epidermis and dermis, which permits quantification of skin layer-specific scar characteristics. This differentiation may allow assessors to observe and understand the pathological mechanisms of individual scars and adjust treatment protocols accordingly. (24, 26-31) Additionally, B-mode ultrasound is commonly used as the basis for other imaging methods, such as colour Doppler ultrasound or elastography, which can allow quantification of additional scar characteristics, such as their elastic properties. (26-29, 32, 33)

Despite the clinical advantages of B-mode ultrasound for scar thickness measurement, methods are poorly reported and lack standardisation in the literature. This casts doubt on the validity of clinical decision-making in measurement-based care initiatives (e.g., setting depth of AFCO$_2$ penetration) informed by research findings (e.g., response to treatment) where ultrasound measurements are used. (34) Lack of standardisation also makes between-study comparison, such as systematic reviews and meta-analyses, difficult, (35) and poor methodological reporting hampers the ability to accurately replicate findings. This scoping review focusses on mapping and identifying gaps in ultrasound methods and evaluation reported in the current literature along the research-to-clinical practice pipeline. (36) Methodological considerations for people performing ultrasound scar thickness measurements, including practitioners (herein termed assessors) using ultrasound in clinical practice are presented based on the review findings.

METHODS:

Protocol Publication and Review Structure:

The protocol for this review has been published *a priori*. (37) This scoping review was conducted and is reported according to the Arksey and O'Malley (2005) (38) framework. The steps outlined in this framework are: 1) identifying the research question; 2) identifying relevant records; 3) selecting appropriate records; 4) charting extracted data; and 5) collating, summarising and reporting the results. (38)

Research Question:

The primary question of this scoping review was: "What do we know and not know about the measurement of traumatic cutaneous scar thickness using ultrasound?" This question was addressed through exploration of: methods used; reliability and measurement error; clinical, health service, implementation and feasibility outcomes; factors influencing ultrasound imaging and measurement methods; strengths and limitations of measurement methods; and use of measurement guidelines and/or frameworks. While the focus of this review was the measurement of traumatic cutaneous scar thickness with ultrasound, methods used to measure the thickness of unscarred skin were reported where these were used in combination with measurement of scar thickness (e.g., as control or comparator measurements).

Identifying Relevant Records:

A standardised search strategy was developed and piloted with the assistance of a medical librarian using the concepts 'ultrasound', 'skin', 'thickness' and 'measure', with associated terms and truncations (supplementary box 1). Ovid MEDLINE, Embase, Cumulative Index of Nursing and Allied Health Literature (CINAHL) and Web of Science electronic databases were searched from conception to identify original studies (date last searched 27th May 2022).

The phrase 'ultrasound scar thickness measurement' was used to conduct additional searches in 1) Google Scholar, and 2) Google to identify original studies in grey literature, and studies not identified in database searches. Title and abstract searches in Google Scholar and Google were limited to the first 200 results. (39)

Record Selection:

Following de-duplication, six reviewers screened records using Covidence (Veritas Health Innovation, Melbourne, Australia; available at www.covidence.org) for eligibility according to the inclusion criteria (Table 1). Both peer-reviewed journal articles and abstracts were included to ensure that all the available and most recent methodological information was obtained. (40) Data collected from peer-reviewed journal articles was considered the primary source of data, with information from abstracts used to confirm or extend the journal data. The inclusion of abstracts will assist future authors to further investigate the information presented as full texts may become available. During both title and abstract and full text screening, one researcher (BM) screened all records as a single reviewer, while other researchers (MS, TM, TR, BD and ZT) screened records as a second reviewer. Conflicts were resolved through discussion between at least two authors to reach agreement. A third author was used as a tiebreaker where agreement could not be reached.

Table 1. Inclusion and exclusion criteria for studies included in the scoping review.

Inclusion	Exclusion
• Traumatic scars measured with ultrasound based on B-mode ultrasound (including high-frequency, ultra-high-frequency and Doppler) • Measurements taken of living, human individuals • Measurement of traumatic cutaneous scarring arising from penetration of the skin with sharp objects (including surgery or vaccination), or as a result of burns, (including thermal, chemical or friction) • Articles written in English, or with English abstracts	• Reviews, discussion papers, opinion pieces • Measurement of non-traumatic scars (e.g., acne scars). Where non-traumatic scars measured along with burn scars, these were included • Measurement of skin thickness in non-traumatic conditions (e.g., diabetes) • Measurement of skin thickness where there is no cutaneous involvement in the trauma (e.g., traumatic brain injury) • Measurement using A-mode ultrasound

Charting the Data:

The data extraction table was developed in Microsoft Excel and piloted by two authors (BM and ZT) through independent extraction and comparison of data from two records. The table was then modified to include the scar characteristics (e.g., fibrosis, oedema) measured, measurer/assessor training, the number of measurements taken and funding sources

(Supplementary Table 1). Full text data extraction was completed by four authors (BM, MS, TM and ZT). An additional author (BD) independently extracted data from five randomly selected records, which was compared to data extracted by other authors. Minimal differences between data extracted by the independent author and that by other authors were observed, thus further independent extraction was not performed. As is typical in scoping reviews, the certainty or quality of evidence was not appraised. (38)

The research-to-practice pipeline published by the Australian Government Department of Health and Aged Care Medical Research Future Fund (figure 1) was used to categorise each included record based on their stated aims into one of the four phases. (36) Studies related to phase 1 of this pipeline, basic research, were only included in this review when data on scar or skin thickness pertained to human participants (table 1). Phase 2 of this pipeline included randomised controlled trials, while phase 3 included pragmatic and observational studies conducted outside randomised controlled trials. The final phase of this pipeline (phase 4) indicates initiatives used in routine clinical practice.

Where clinical (e.g., treatment satisfaction, scar symptoms), health service (e.g., efficiency, safety, effectiveness, equity, patient-centredness and timeliness) and implementation (e.g., acceptability, adoption, appropriateness, fidelity, cost, penetration and sustainability) outcomes were addressed, they were reported and defined according to Proctor *et al*. (41). For example, in the context of this scoping review, acceptability is defined as the level to which ultrasound is palatable amongst stakeholders (e.g., assessors), appropriateness is the perceived fit of ultrasound within regular clinical practice, and fidelity is the degree to which ultrasound is used in the way it was initially described. (41) Measurement instrument-specific feasibility outcomes defined by Prinsen *et al*. (42) are reported in the current review. These outcomes included ease of administration, standardisation, completion time, instrument cost and availability, and ease of score calculation. (42) Reliability and measurement error were defined according to COnsensus-based Standards for the selection of health Measurement INstruments (COSMIN) tools. (43, 44) Measurements with an intraclass correlation coefficient (ICC) of 0.7 or greater were considered reliable. (44) Measurement error was assessed by comparing the reported standard error of the measurement (SEM) with the reported smallest detectable change (SDC). Where the reported measurement error was smaller than the reported smallest detectable change, it was interpreted as indicating real change or variance can be detected, and that change or variance is not a result of error. (44)

Patient and Public Involvement

There was no patient and/or public involvement in the design, conduct, reporting or dissemination of information in this scoping review.

RESULTS:

Electronic database searches identified 9309 records. After removal of 3703 duplicate records, the titles and abstracts of 5606 records were screened for relevance according to the inclusion criteria (Table 1). Following full-text screening, 104 records proceeded to data extraction. Searches in Google and Google Scholar identified an additional 14 records, providing a total of 118 records for data extraction. Search and screening results are presented according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram (supplementary figure 1). (45)

Record Characteristics:

Of the 118 records included in this review, 82 were journal articles (69%) and 36 were abstracts (31%) (Table 2), representing a total of 5213 participants (range 1-438; mode 20 participants per record). Adults aged 18 years and older were the most highly represented age group reported in articles (n = 43 articles; 52% of articles), (17, 26, 29, 46-85) while most abstracts did not report the age group measured (n = 25 abstracts; 69% of abstracts). (86-110)

The most common scar type measured was burn scars in both journal articles (n = 43 articles; 52% of articles), (17, 22-24, 27, 47, 57-59, 61, 62, 64-67, 71-75, 81, 82, 84, 111-130) and abstracts (n = 23 abstracts; 64% of abstracts) (28, 30, 86-88, 91-94, 96, 98, 102-106, 131-135) (Table 2). Most identified articles used ultrasound measurement of scar thickness as part of research initiatives, and were categorised as either phase 2 (n = 50 articles; 61% of articles) (17, 22, 26, 31, 46-49, 51-56, 61, 63-65, 67, 69-71, 74-76, 78, 81, 83, 84, 111, 112, 114, 115, 117, 124-127, 129, 130, 136-145) or phase 3 (n = 30 articles; 37% of articles). (23, 24, 27, 29, 50, 57-60, 62, 66, 68, 72, 73, 77, 79, 80, 82, 85, 116, 118, 120-123, 128, 146-149) on the research-to-practice pipeline. (36) Phase 2 was also the most common phase represented by abstracts (n = 21; 58% of abstracts), (86, 88, 91, 93, 95, 97, 99-104, 106-108, 131-134, 150, 151) followed by phase 3 (n = 15 abstracts; 42% of abstracts). (28, 30, 87, 89, 90, 94, 96, 98, 105, 109, 110, 135, 152-154) Phase 4 was addressed by two articles (2% of articles) (113, 119) and one abstract (2% of abstracts), (92) which used ultrasound to measure treatment response to an intervention already used in routine clinical practice, including compression garments (113, 119) and CO_2 fractional laser. (92) No records pertained to phase 1.

Table 2. Summary of characteristics of records included in this review*

Characteristic	**Category**	**Number of Records (Translational Pipeline Phase 2[*])**	**Number of Records (Translational Pipeline Phase 3[*])**	**Number of Records (Translational Pipeline Phase 4[*])**
Journal Articles				
Funding Source	Commercial	2	1	1
	Non-commercial	23	13	0
	Commercial & Non-commercial	2	1	1
	No funding	6	3	0
	Not reported	16	12	0
Population Type	Adult	27	16	0
	Paediatric	6	4	0
	Paediatric and Adult	13	7	2
	Not reported	3	3	0
Scar Aetiology	Burn	22	18	1
	Surgical[†]	5	2	0
	Mixed	10	3	0
	Not specified	12	7	0
Abstracts				
Funding Source	Commercial	0	0	0
	Non-commercial	3	1	0
	Commercial & Non-commercial	0	0	0
	No funding	0	0	0
	Not reported	17	14	1
Population Type	Adult	1	2	0
	Paediatric	0	3	0
	Paediatric and Adult	4	1	0
	Not reported	15	9	1
Scar Aetiology	Burn	12	10	1
	Surgical[†]	1	2	0
	Mixed	2	1	0
	Not specified	5	2	0

Legend: Paediatric: measurement of patients under the age of 18; Adult: measurement of patients aged 18 years or older; Burn: scars caused by thermal, chemical or friction injury; Surgical: scars caused by surgical procedures (including biopsies); Mixed: scars of included record were of mixed origin (e.g., burn and acne)

Footnotes: [*]Stage in the research to clinical practice translational pipeline, as defined by the Australian Government Department of Health and Aged Care (36); [†]Type of surgery defined in supplementary table 2

* A breakdown of each characteristic per record is presented in Supplementary Table 2

Methods used to measure traumatic cutaneous scar thickness:

B-mode, including high-frequency B-mode ultrasound (i.e., ≥ 20 MHz) was the most commonly reported ultrasound type in the included articles (n = 56; 68% of articles) (17, 22-24, 26, 29, 31, 46-49, 53, 54, 56, 57, 59, 60, 64, 65, 67, 69-78, 80-82, 84, 85, 111, 112, 114, 116-118, 120, 122, 123, 126-130, 138, 139, 141, 142, 144-146, 149), while most abstracts did not report the type of ultrasound used (n = 22; 61% of abstracts) (86, 87, 92-98, 101, 103, 105, 106, 108, 131-134, 150-153) (Table 3). Specialised B-mode ultrasound devices, including the Tissue Ultrasound Palpation System (TUPS; a B-mode ultrasound transducer in-series with a load cell to allow measured compression of the skin), (68, 99, 100, 124) and colour Doppler ultrasound, (52, 149) were used in six records (Table 3).

Table 3. Summary of measurement methods used in included record*

Characteristic	Parameters	Number of Records
Journal Articles		
Ultrasound Type	B-mode	24
	Midrange	2
	High-frequency	29
	Other	4
	Not reported	22
Measurement Parameters	Epidermal	0
	Dermal	4
	Epidermal & dermal	2
	Combined epidermal & dermal	32
	Other	3
	Not reported	40
Scar characteristic measured	Fibrosis	27
	Oedema	1
	Fibrosis & oedema	10
	Other	1
	Not reported	42
Abstracts		
Ultrasound Type	B-mode	3
	Midrange	0
	High-frequency	9
	Other	3
	Not reported	21
Measurement Parameters	Epidermal	0
	Dermal	1
	Epidermal & dermal	4
	Combined epidermal & dermal	1
	Other	1
	Not reported	29
Scar characteristic measured	Fibrosis	2
	Oedema	0
	Fibrosis & oedema	0
	Other	0
	Not reported	34

Legend: B-mode: brightness-mode ultrasound (<20 MHz); High-frequency: High-frequency B-mode ultrasound (>20 MHz); Other: fields are expanded with additional detail in supplementary table 3

*A full summary of each included record is available in supplementary table 3

The type of scar and skin thickness measurement (i.e., thickness of the dermis, epidermis, or combined epidermal and dermal measurement) was reported in 39 records (33%) (Table 3). Where reported, combined measurement of epidermal and dermal thickness was the most common method used in articles (n = 32; 76% of articles reporting skin measurement type). (17, 22-24, 27, 29, 50, 53, 56-58, 60, 64-66, 70, 72-77, 80-82, 114, 116, 118, 122, 126, 127, 130, 139, 146, 148) Separate epidermal and/or dermal thickness measurements were reported in seven journal articles (17% of articles reporting skin thickness measurement type). (26, 47, 48, 52, 53, 71, 118) Of these records, two authors provided a rationale for this decision: each skin layer provided different information on the scar; (26) or responded differently to treatment. (67, 71) Most abstracts did not report the type of skin measurement used (n = 30; 83% of abstracts). (28, 30, 91-101, 103-110, 131-134, 150-154)

Three articles (4% of articles) (47, 110, 111) and one abstract (3% of abstracts) (28) directly reported that fibrosis was the scar characteristic targeted by the measurement. One of these records also quantified hair follicle density to assess the difference between scared and unscarred skin. (47) An additional 25 articles (30% of articles) (17, 46, 52, 53, 56, 63-65, 67, 70, 79, 80, 83, 84, 112, 120, 123, 125-127, 140, 142, 145, 148, 149, 155) and one abstract (3% of abstracts) (110) made indirect reference (i.e., within the introduction or discussion) to the measurement of fibrosis. Ten journal articles (12%) made indirect reference to the measurement of both oedema and fibrosis, (31, 54, 55, 71, 74, 76-78, 138, 144) and one record made indirect reference to the measurement of oedema. (59)

Additional objective and/or subjective measurement methods were employed alongside ultrasound measurement in 72 articles (88% of articles) (17, 22, 24, 26, 29, 31, 46-53, 55-57, 60-70, 72-81, 83-85, 111-122, 124-130, 136-142, 144, 145, 147-149) and 31 abstracts (86% of abstracts) (86, 88, 89, 91-95, 97-110, 131-134, 150, 151, 153, 154) (Supplementary Table 4). All three phase 4 studies involving implementation in routine clinical practice utilised additional measurements. (92, 113, 119) The additional objective measurements used in included records were elastography (elasticity), cutometric assessment (pliability) and Doppler ultrasound (vascularity). The additional subjective measurements were conducted using clinician-based rating scales (e.g., Vancouver Scar Scale or modified Vancouver Scar Scale) or Patient Reported Outcome Measures. The Vancouver Scar Scale was used in 35 articles (43% of articles) (17, 31, 46, 47, 49, 50, 52, 55, 57, 61-64, 66-70, 73, 85, 111, 112, 114, 116, 118, 121, 124, 128, 130, 136-138, 140-142) and 11 abstracts (31% of abstracts) (88, 91, 92, 98-100, 107, 134, 150, 151, 153). Patient-reported outcome measures (PROMs) were used in 27 articles (33% of articles) and 11 abstracts (31% of abstracts). (46, 53, 56, 57, 60, 72-75, 85, 91, 94, 97, 101-106, 111, 112, 114, 115, 117, 118, 120, 122, 129, 131-133, 138, 140, 141, 148, 150, 151, 153, 154) Of the records that reported using PROMs, the most commonly used was the patient report of the Patient and Observer Scar Assessment Scale (POSAS), used in 17 articles (63% of articles reporting use of PROMs) (17, 22, 46, 50, 53, 61, 62, 64, 76, 77, 79, 114, 121, 125-127, 147) and 8 abstracts (73% of abstracts reporting use of PROMs) (91, 93, 102, 104, 106, 132, 153) (Supplementary Table 4). In most cases, additional measurement methods were used to supplement ultrasound thickness measurements as research outcomes. In some records (n = 16; 14% of records), however, ultrasound was compared with histology, POSAS, dermoscopy, VSS and modified VSS, clinical assessment, modified Seattle Scar Scale, high-definition optical coherence tomography, 3D camera, immunohistochemistry, and immunohistomorphometry. (17, 24, 26, 29, 31, 50, 51, 64, 73, 77, 86, 95, 110, 120, 124, 149) Where the effectiveness of ultrasound was judged against other methods, it was only found to be inadequate against histology. (26, 86)

Methods used to relocate the scar for repeated measurements were reported in 34 records (29%) (Supplementary Table 3). The most common relocation method was tracing the outline or boundaries of the scar on a transparent or translucent sheet (n = 14 articles; 35% of articles reporting scar relocation), (23, 49, 65, 74, 81, 115, 116, 120, 124, 125, 153) occasionally including prominent or bony landmarks close to the scar. (23, 24, 72, 73, 123) Photographs (n = 10 articles; 25% of articles reporting relocation and n = 1 abstract) and linear measurements from defined points or anatomical landmarks on or around the scar (n = 4 articles; 10% of articles reporting relocation) were also used for scar relocation. The 'worst' or 'thickest' part of the scar, as determined by patients or assessors, was chosen as the measurement site in 14 journal articles (35% of journal articles reporting relocation) (23, 31, 52, 54, 57, 61, 62, 67, 126, 127, 138, 141, 148, 155) and one abstract. (105)

Measurement of unscarred skin, either contralateral or adjacent to the scar, was performed in 32 articles (39% of articles%) (17, 22-24, 27, 29, 46-48, 50, 51, 53, 56-60, 64, 72, 73, 80, 81, 85, 114, 118, 120-122, 128, 145, 146, 148) and 7 abstracts (19% of abstracts) (28, 94, 95, 150, 151, 153, 154) These measurements were primarily used as controls or comparators to scar measurements (n = 27, 69% of records reporting unscarred skin measurement). (17, 22, 23, 28, 29, 47, 48, 51, 53, 56-60, 64, 67, 73, 80, 85, 95, 118, 120, 122, 128, 146, 148, 153, 154) Additionally, four records (10% of records reporting unscarred skin measurement) evaluating treatment efficacy measured both unaffected skin thickness and the thickness of a 'control' or untreated scar. (46, 74, 94, 114) All instances where additional ultrasound measurements were taken of unscarred skin or untreated scars were reported as part of research initiatives aligning with phases 2 and 3 of the research-to-practice pipeline (figure 1). (36)

Reliability and measurement error

Reliability was calculated for both scarred and unscarred skin in 13 articles (16% of articles) and two abstracts (5% of abstracts), and was generally considered acceptable (Supplementary

Table 5). This included inter-rater reliability (n = 5; 4% of articles), (54, 64, 73, 120, 137) intra-rater reliability (n = 3; 4% of journal articles), (22, 23, 65) and both inter- and intra-rater reliability (n = 7; 6%; including 2 abstracts) (17, 24, 57, 82, 87, 105, 124). The intraclass correlation coefficient (ICC) was the most commonly reported reliability statistic (n = 10; 8% of records, including one abstract), (17, 24, 57, 64, 65, 73, 82, 87, 120, 124) where it was reported for both scar and unscarred skin measurements in four articles (5% of articles). (17, 24, 57, 73) The reported combined thickness (i.e., epidermal and dermal) ICCs for inter-rater reliability of scarred skin ranged from 0.82 to 0.985, while the inter-rater ICC for the measurement of unscarred skin ranged from 0.33 to 0.98, with one of the four records reporting an ICC below the threshold value of 0.7 (ICC = 0.33) (24) and one record simply reported that the inter-rater ICC for scarred skin was “acceptable to high”. (64) The reported intra-rater reliability for combined thickness measurements of scarred skin ranged from 0.89 to 0.983, and for unscarred skin ranged from 0.61 to 0.982, with one record reporting an ICC below the threshold of 0.7 (ICC = 0.61). (24) One record reported both the inter- and intra-rater ICCs for individual epidermal (inter-rater ICC = 0.297; intra-rater ICC = 0.809) and dermal (inter-rater ICC = 0.991; intra-rater ICC = 0.991) scar thickness measurement. (87) Four articles (5% of articles) reporting reliability used Pearson’s R, an undisclosed method, or description (e.g., high) as detailed in supplementary table 2. (22, 54, 105, 137)

Measurement error for inter-rater and intra-rater reliability of combined, epidermal or dermal thickness was reported in four articles (5% of articles) and one abstract using standard error of the measurement (SEM). The inter-rater SEM for the combined epidermal and dermal thickness of scarred skin ranged from 0.11 mm to 0.5 mm, and the intra-rater SEMs ranged from 0.18 to 0.52 mm. Individual records reported SEM values for unscarred skin, and separate epidermal and dermal measurements, available in Supplementary Table 5. (17, 23, 24, 82, 87) Only one record reported calculation of the smallest detectable change (SDC). In that record the inter-and intra-rater SDC was calculated for both scarred and unscarred skin. The scarred skin SDCs were 1.4 mm (inter-rater) and 0.6 mm (intra-rater), and unscarred skin SDCs were 0.8 mm (inter-rater) and 0.5 mm (intra-rater). (24) The reported SEMs were all close to or below the largest SDC value reported. This finding may indicate that ultrasound can detect true variance in scar thickness above measurement error for traumatic scar and skin thickness.

Of the records that reported reliability and measurement error, measurements were taken by practitioners with varying clinical expertise and roles within the treating team. These included therapists, nurses and doctors, sometimes under the supervision of trained radiologists. One record reported that 3 assessors received 3 hours of training, and conducted 10 assessments using the study protocol before the study began. (57)

Clinical, health service, implementation and feasibility outcomes:

No record specifically investigated clinical, health service, implementation or feasibility outcomes of ultrasound as a measurement-based-care initiative. Ultrasound was used to assess the clinical outcomes of scar treatment initiatives in all included records. Clinical, health service, implementation and feasibility outcomes related to ultrasound measurement were, however, reported in 53 journal articles (17, 22-24, 26, 27, 31, 46-48, 50, 51, 54, 56-61, 63-66, 69-75, 77, 80, 82, 113-116, 119, 120, 122-124, 128, 129, 138, 142-144, 148, 149, 155) and 14 abstracts (28, 86, 87, 89, 90, 95, 96, 102, 105, 107, 109, 110, 152, 153) that focused on scar treatments.

The clinical outcome of patient satisfaction related to ultrasound measurement was only reported in one journal article. Whilst patient satisfaction was not directly measured in that record, a proxy measure of satisfaction was reported by the authors stating that no paediatric patient or their caregiver refused ultrasound measurement once the purpose was explained. (24)

Timeliness was the only reported health service outcome, reported as the time required to take ultrasound measurements. Where reported in three journal articles, this was short, taking between one to five minutes. (24, 27, 122)

The most common implementation outcomes reported in the identified records were fidelity, acceptability and appropriateness. Fidelity to the measurement method was reported through the use of experienced or trained assessors (n = 6 journal articles; n = 1 abstract), (24, 57, 58, 87, 142, 144, 148) and/or utilising the same assessor/s for all measurement sessions (n = 5 journal articles; 6% of included journal articles). (24, 61, 138, 144, 148) Differences between intended and actual measurement methods were not discussed. The training and/or experience of the assessors was discussed in 24 records (23 journal articles and 1 abstract), (17, 23, 24, 27, 51, 56-59, 63-66, 71, 73, 115, 116, 120, 123, 124, 138, 144, 149, 153) where measurements were either taken by a clinician (n = 13; 54% of records reporting training), (17, 23, 24, 58, 59, 64-67, 71, 120, 124, 141) members of the research team (n = 6; 25% of records reporting training), (57, 63, 73, 115, 123, 144) or by specialist sonographers and/or radiologists (n = 5, including one abstract; 21% of records reporting training). (56, 116, 138, 149, 153) Only one record reported on fidelity in the context of routine clinical practice. In this instance, ultrasound was conducted in the department of radiology, however the role or training of the staff was not reported. (119)

The acceptability and appropriateness of the ultrasound methods used in individual records were generally based on author opinion and outlined in the discussion. Acceptability was reported in 26 records (23 journal articles and 3 abstracts), (17, 22-24, 26-28, 31, 57, 64, 70, 74, 75, 77, 80, 82, 86, 96, 116, 119, 120, 122, 124, 143, 149, 155) including for paediatric populations, where one record reported potential difficulty in measuring this population, (22) contrasting that which reported that measurement was acceptable to both children and their caregivers. (24) One record reported acceptability where the intervention being analysed by ultrasound was already part of routine clinical practice. In this instance, the authors referenced additional publications which stated that ultrasound had an accuracy of 0.5 mm, which was judged by the authors to be sufficient for assessment of scar thickness. (24, 27, 119, 122) Potential difficulty was identified in the measurement of open wounds, (24) and traditionally hard-to-reach areas (such as the axillae or groin). (22)

The appropriateness of the ultrasound methods was reported in 35 journal articles (43% of included journal articles) (22, 24, 26, 27, 31, 46-48, 50, 54, 57, 60, 61, 64-66, 69, 72-75, 77, 80, 82, 113, 114, 116, 119, 120, 122, 124, 128, 148, 149, 155) and 11 abstracts (31% of included abstracts) (86, 87, 89, 90, 95, 102, 105, 107, 109, 110, 152), where it was generally addressed in the discussion. Of these records, two (4% of records reporting appropriateness) determined that ultrasound was not appropriate for scar measurement. The first stated that it was too inaccurate and complex; (86) and the second, which reported on initiatives within routine clinical practice, determined that the minimum resolution of the Diasonography ultrasonic scanner (Nuclear Enterprises, Edinburgh, UK) precluded its use in scars thinner than 3mm. (113)

The feasibility of ultrasound was reported in 12 journal articles (15% of included journal articles). (22, 24, 26, 46, 57, 70, 80, 119, 120, 124, 129) Five records considered ultrasound not feasible for scar measurements. The rationale presented included high-frequency 20 MHz ultrasound having an inadequate penetration depth; (26, 57) and ultrasound measurement and training of investigators requiring too much time (as reported in one record in phase 4 of the research-to-practice pipeline). (22, 119, 120) Another factor identified as precluding feasibility was the inability to consistently relocate the measurement site. (24) Conversely, one record reported ultrasound to be feasible in combination with Vancouver Scar Scale (VSS) measurement, (70) and another stated that ultrasound was able to distinguish between subcutaneous fat and muscle, which was interpreted by the authors of that record to mean that skin thickness measurements were accurate. (129) The majority (n = 11; 92%) of the records reporting feasibility were research initiatives in phase 2 or 3 of the research to practice pipeline. One record examined feasibility in the context of routine clinical practice (i.e., phase 4; figure 1), (119) where it was determined that ultrasound was not suitable for use in their twelve-year longitudinal study due to changes in staff, equipment and software over such a long time period, which introduced additional variables to the measurement process that were impossible to control. (119)

Factors influencing ultrasound images and measurement methods:

The only factor that was reported to influence the imaging and measurement methods was the measurement of scars with open wounds. This was reported in one record, which determined that ultrasound and ultrasound gel was unsuitable in this instance. The authors of that record suggested the use of a flexible transparent plastic wrap, which is placed over the measurement area prior to measurement with ultrasound. (24)

Reported strengths and limitations of the measurement methods:

The safety, practicality, objectivity, versatility, reliability and non-invasive nature of ultrasound were all reported as strengths of the measurement method. (22, 27-29, 47, 50, 57, 61, 64, 77, 78, 80, 82, 87, 89, 95, 96, 105, 107, 109, 119, 123, 124, 129, 139, 148) When compared to other subjective or clinical measurement methods (e.g., VSS) and 3D camera, ultrasound was viewed as the superior measurement method of scar and skin thickness, due to its improved accuracy, greater sensitivity to change and objectivity. (24, 64, 73, 116, 120) The ability of ultrasound to differentiate between scarred and unscarred skin was also highlighted (n = 4; 3%), (47, 60, 72, 122) as was the versatility of ultrasound in its ability to measure a variety of anatomical areas and be used with child participants (i.e., <18 years) (n = 2; 2%). (22, 149)

The poor correlation between ultrasound and histological thickness measurements, (86) and the established inverse relationship between ultrasound penetration depth and the resolution of superficial structures were identified as limitations of ultrasound in the measurement of scar thickness. (26, 27, 77, 80, 89, 113, 149) This may be an evidence gap worth exploring in more depth. One record, reporting on a longitudinal study that was conducted over twelve years, reported that the continuous development of ultrasound software and hardware over that time limited the usefulness of ultrasound. (119) Despite being reported elsewhere as acceptable (i.e., between one to five minutes (24, 27, 122)), one record reported that the time-consuming nature of measurement and the requirement for assessors to be trained in the operation of, and techniques required for, ultrasonography was a limitation of the method. (120) Methodologically, concerns were raised around the pressure caused by application of the ultrasound transducer to the skin, and how that may influence thickness measurement. (61, 62, 123, 124) The size of the transducer head relative to the size of scars was also considered a potential limitation, as multiple measurements are required for quantification of larger scars. (57) Finally, it was recognised that there may be a difference between changes to the scar that can be measured by ultrasound, and what is felt and/or experienced by the patient. (75, 80, 126, 127) It was suggested that changes that are detectable by ultrasound may be smaller than those able to be detected by patients. In patients with burn scars, a minimum change in scar thickness of between 1 to 6 mm measured by ultrasound, has been reported to be required before a patient may report noticing any difference to their scar thickness. (24, 75) While further research is required to allow generalisation of these findings to other scar aetiologies, this indicates that a holistic approach to scar thickness using the patient's opinion as well as objective measurement through ultrasound may be beneficial.

Guidelines or frameworks used to guide the measurement methods:

No records reported using any guidelines or frameworks to inform their measurement methods. One record utilised suggestions from The American Wound Healing Society to support the measurement of contralateral, unscarred skin thickness on the same individual as a control or comparator. (75)

Methodological Considerations:

Based on the ultrasound methods and outcomes identified in this review, a list of methodological considerations have been compiled (Supplementary Table 6). These are intended to guide the decision-making and methodological reporting of researchers and/or clinicians undertaking scar or skin thickness ultrasound measurement.

DISCUSSION:

This review mapped the methods used in the published literature to measure traumatic scar thickness using ultrasound across the research-to-practice translational pipeline. No record reported their methods with sufficient detail to allow them to be independently replicated. Overall, there was a lack of consistent rationale underpinning which skin layers (i.e., epidermis, dermis and combined) were measured, and little consideration was given to the training and experience required by assessors. The included records mainly aligned with the second and third phases of the research-to-practice pipeline (figure 1), with only three records (2 articles and 1 abstract) reporting the use of ultrasound in routine clinical practice (phase 4). (92, 113, 119). The paucity of records aligning with phase four studies (use in clinical practice) suggests a translational gap from research to regular clinical practice. There are two likely explanations for this: 1) that ultrasound is most commonly used as an outcome measure for research initiatives and is not regularly used to evaluate care once treatments are implemented into routine clinical practice; or 2) that use of ultrasound in routine clinical practice is not reported or evaluated, as routine clinical practice is rarely published.

Searching of grey literature was conducted in an attempt to identify clinical practice documents, however none were located. Surveys of health service departments may be the best method of identifying ultrasound methods used in regular clinical practice as part of future research. While some records reported using additional subjective and objective measurement methods in addition to ultrasound, none used these methods to determine the criterion validity of the ultrasound for scar thickness measurement. This is another evidence gap that should be addressed.

While efforts have been made to standardise ultrasound measurement procedures elsewhere in dermatology (including tumours, cancers, vascular anomalies, and systemic sclerosis (34, 35)), this same effort has not yet extended to the measurement of traumatic scarring. Methodological standardisation has the potential to increase confidence in the use of ultrasound as the basis of measurement-based care initiatives for clinical decision-making, allowing patient care and scar treatments to be tailored towards individual needs. (62, 147, 156) Standardising the core methodological components of ultrasound measurement of scar thickness, or at the very least, creating a standardised framework for methodological decision-making, may support implementation of ultrasound measurement into routine clinical practice, supported by strategies to overcome barriers to implementation at local sites. (157)

This review identified novel insights into the identification of the composition of cutaneous scars using ultrasound, and highlighted the apparent lack of consistent understanding of, or rationale behind, what scar thickness characteristics were being measured. Fibrosis is generally understood to be the primary cause of scar thickness through the deposition of excessive extracellular matrix proteins such as collagen. (158, 159) This has been confirmed through histological analysis, which has shown the presence of excess collagen and other extracellular matrix proteins in the dermis of hypertrophic scars. (160, 161) An additional method for assessing the effects of scarring on the dermis, as identified by one record in this review, (47) is through quantification of the presence and density of hair follicles. This quantification may serve as a method of differentiation between scarred and physiological skin, and may also serve as a measure of skin function. (47) What is less understood, and perhaps largely overlooked, is the function of the epidermis in scar thickness. In the one record identified in this review that directly report the measurement of the epidermis, the authors noted that the measurement quantified the presence of oedema. (55) This was further supported by two records that noted that the epidermis and dermis responded differently to treatment, (67, 71) indicating that there is likely a difference in the composition of the scar between these skin layers. Cutaneous oedema has been observed using high-frequency ultrasound in other pathologies, including atopic dermatitis and skin ageing, where it is characterised by the presence of a sub-epidermal low echogenic band (SLEB), a hyperechoic band at the dermoepidermal junction. (162) Understanding the interplay between epidermal oedema, dermal fibrosis and the presence and density of hair follicles may result in an increased understanding of the mechanisms and treatment responses of cutaneous scarring. With better understanding, more targeted scar treatments that inform a greater understanding of scar responsivity may arise.

Another important, but potential limiting factor for the use of ultrasound to measure scar thickness raised in this review is the training and/or experience required of assessors, and the ramifications this likely has on the reliability of measurements and interpretation. (163) This review identified 24 records where assessor experience was discussed, however none made any recommendations on the optimal training and/or experience. Identifying the training requirements of assessors may prove an important step towards more widespread implementation of reliable ultrasound scar thickness measurement in research trials and as the basis for measurement-based care in routine clinical practice. (164) A panel of dermatological and ultrasound experts has previously recommended that a physician with a minimum of 300 examinations per year should hold responsibility for ultrasound measurements. (34) It has also been suggested that training existing members of clinical teams and standardising measurement method/s may be the most effective way to achieve minimum reliability standards under clinical conditions. This could allow measurement to be reliably conducted within an outpatient clinic setting by a number of healthcare providers assisting workflow, negating the requirement for patients to wait for an experienced radiographer. (24, 164) In the current review, reliability estimates were generally acceptable but were tested under research conditions. The diverse experience and expertise of assessors, where reported for the reliability estimates, means that the acceptable reliability results should be generalisable to most clinical teams, as therapists, doctors and nurses were all included. The cumulative sample size of all reliability studies also supports this generalisation; however each team should perform their own reliability estimates before conducting ultrasound thickness measurements.

Study Limitations:

Only articles available in English or with an English abstract were considered for inclusion and data extraction, which may have resulted in the omission of eligible information. Data extraction was completed on the English abstracts of two non-English articles that were available electronically, however the non-English articles themselves were not available to the authors, and thus could not be analysed. Based on the number of records included in this review, however, it is unlikely that this would have impacted the review findings. It is acknowledged that methods reported in included abstracts may not be fully reproducible, due to their brevity. Thus, findings were reported separately to articles. An additional limitation was that authors of included records were not contacted to provide clarification or further information, as this was not feasible given the number of results identified. It should also be acknowledged that the included records were not designed to align with the specific aims of this review, which likely explains some of the lack of reporting on outcomes of interest in our review, particularly clinical, health service and implementation outcomes. Furthermore, as this review relied on published information (including grey literature), routine practices employed within organisations may not have been considered and unpublished industry sponsored reports may not have been identified.

It is also important to consider the limitations of ultrasound itself for the holistic quantification of cutaneous scarring. Ultrasound transducers are generally small, meaning that it is difficult to assess the entirety of a scar, necessitating multiple measurements. (165) Additionally, thickness is often not the only scar parameter of clinical or research interest. It has therefore been recommended that multi-modal measurement techniques are employed, which include both subjective and objective measurements. (166, 167) However, use of these methods may be challenging in routine clinical practice, due to the length of time and training required. Thus, feasibility and implementation outcomes are of importance in evaluating measurement-based care initiatives involving ultrasound alone or multimodal measurement tools in scar care practice – a field in its infancy based on this review.

Future Directions:

It is intended that the results of this review will be used to inform the creation of a Delphi consensus study, leading to the formation of a guideline for the measurement of traumatic scar thickness using ultrasound. This guideline can then be used by researchers and clinicians to standardise the measurement of scars. In preparation for this study, we have provided a list of methodological considerations for assessors or practitioners when planning to conduct scar thickness measurements with ultrasound (Supplementary Table 6). Future research could also investigate aspects that were beyond the scope of this review including factors influencing the implementation of ultrasound-based care initiatives, strategies to support implementation, and how research-based initiatives could be applied in practice. Further studies are needed that compare SDCs to SEMs to interpret reliability estimates to confirm our interpretation that ultrasound may have the ability to detect true change or variance in scar thickness above measurement error, which was based on the SDC reported by a single study. Our interpretation is supported by mostly acceptable reliability estimates of ultrasound thickness for other cutaneous conditions. (168, 169) Additional investigations should also be conducted to determine the criterion validity of ultrasound as a measure for scar thickness.

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The authors declare no competing interests. The research presented in this publication was conducted as part of BM’s PhD, and will be included in his thesis for submission to The University of Queensland.

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AUTHOR CONTRIBUTIONS

BM and ZT conceived the project after identifying this area as a knowledge gap in existing literature. BM developed the research questions and study methodology, conducted the literature search, screened all articles and extracted data. Record screening and data extraction was completed by BM, MS, TM, and TR, with additional extraction completed by BD to assess consistency. MS, TM, TR and RK provided advice to BM on the clinical implications of ultrasound measurement. MS, RK and ZT contributed to the supervision of BM as a PhD student. BM drafted the paper, and ZT and MS provided critical appraisal of the drafted manuscript, with further advice provided by TM, TR, BD and RK.

DATA SHARING STATEMENT:

Not applicable

ETHICS APPROVAL STATEMENT:

This study does not involve human participants. No ethics approval was required.

FIGURE LEGENDS:

Figure 1: Research to clinical practice pipeline.

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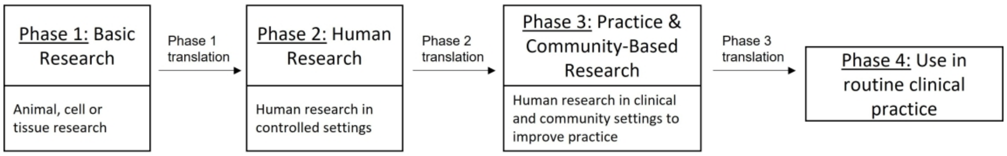


Figure 1: Research to clinical practice pipeline.

275x42mm (330 x 330 DPI)

Supplementary Box 1. Full search strategy for Ovid MEDLINE.

((ultrasound.ti,ab. OR ultra sound.ti,ab. OR sonograph*.ti,ab. OR ultrasonic.ti,ab. OR high-frequency.ti,ab. OR high frequency.ti,ab. OR hfus.ti,ab. OR ultrasonog*.ti,ab. OR exp Ultrasonography/)
AND

((skin.ti,ab. OR epiderm*.ti,ab. OR derm*.ti,ab. OR cutaneous.ti,ab OR scar*.ti,ab OR keloid*.ti,ab OR cicatri*.ti,ab OR exp Skin/ OR exp Dermatology/ OR exp Cicatrix/)

AND

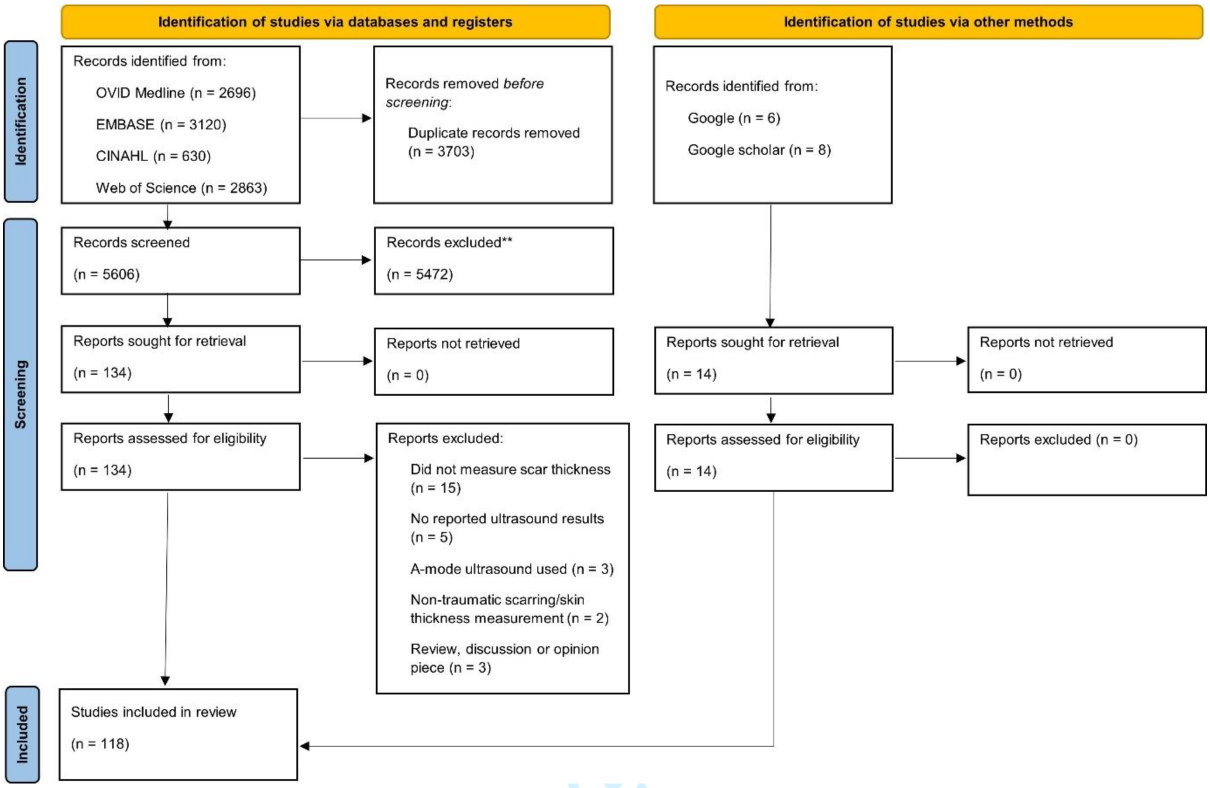
(thickness*.ti,ab. OR thicken*.ti,ab. OR depth.ti,ab. OR volume.ti,ab. OR height.ti,ab. OR vancouver scar scale.ti,ab)

ADJ10

(measure*.ti,ab. OR quantif*.ti,ab. OR calculat*.ti,ab OR estimat*.ti,ab OR assess*.ti,ab. OR determin*.ti,ab. OR evaluat*.ti,ab OR imag*.ti,ab OR exam*.ti,ab)))

NOT (exp animals/ NOT exp humans/)

Legend: ab, abstract (searches the abstract of the publication); adj10, adjacency (search terms must be located within 10 words of one another); exp, explode (used to include all subheadings when searching MeSH headings); ti, title (searches the title of the publication)



Supplementary Figure 1. Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram for this study.

Supplementary Table 1: Extraction categories and fields

Extraction category	Extraction field
Publication details	First author
	Year of publication
	Title of publication
	Country (first author)
	Country (study)
	Country (recruited)
	Publication type (e.g., peer-reviewed journal article, abstract)
	Journal name
	Corresponding author contact details
	Funding source (e.g., commercial, non-commercial)
	Use of scar thickness measurement (e.g., longitudinal study, response to treatment)
Study details	Aim/objective
	Research questions
	Target population/topics
	Study design (e.g., RCT, mixed methods)
	Data and analysis (i.e., statistical methods)
	Removal of scar treatments before ultrasound measurement (e.g., length of time before measurement)
	Reason for measurement (e.g., research, clinical initiative)
	Inclusion/exclusion criteria
	Dates of data collection
	Ultrasound thickness collection methods (e.g., direct collection, collected from medical records)
	Contralateral/unaffected/comparator skin thickness measurement
	Other methods used
	Use of guidelines/frameworks for measurement methods
	How previously published methods/guidelines were used
	Research pipeline stage
	Setting (e.g., inpatient/outpatient clinics)
	Scar type (e.g., burn scar, surgical scar)
Participant details	Number of participants
	Population type (e.g., adult/paediatric)
	Gender ratio
	Patient involvement in thickness determination
	How patients were involved in thickness determination
Ultrasound methods	Ultrasound mode
	Device name and manufacturer
	Frequency used
	Number of measurements taken
	What did researchers report they were measuring (e.g., fibrosis, oedema)
	Anatomical locations/functional measurement units measured
	Patient orientation
	Ultrasound transducer orientation
	Methods used to prevent skin compression
	Measurement site relocation strategies
	Type of skin measurement (i.e., epidermis/dermis/combined)
	Measurer training
Psychometric properties*	Reliability
	Measurement error
Feasibility† outcomes	Time taken for measurement

	Availability of measurement method Ease of administration Number of steps required Number of people required to conduct measurements Considerations for special populations
Implementation[‡] outcomes	Acceptability Adoption Appropriateness Cost Feasibility Fidelity Sustainability
Strengths and limitations of measurement methods	Strengths Limitations Barriers Enablers
Findings	Ultrasound-related findings

[*] Psychometric properties as outlined in the COSMIN Risk of Bias tool to assess the quality of studies on reliability or measurement error of outcome measurement instruments[1]

[†] Feasibility outcomes as per Prinsen *et al*.[2]

[‡] Implementation outcomes as per Proctor *et al*.[3]

Supplementary Table 2. Characteristics of records included in this review. Studies are listed alphabetically by author within the translational pipeline phase.

First Author (year)	Country of Publication	Funding Sources	Sample Size (n)	Population Type	Scar Aetiology	Translational Pipeline Phase*
Journal articles						
Agabalyan (2017)	Canada	Non-commercial	10	Adult	Not specified	2
Alsharnoubi (2018)	Egypt	No funding	15	Paediatric	Burn	2
Alsharnoubi (2018)	Egypt	Not reported	15	Paediatric	Burn	2
Alshehari (2015)	Egypt	Not reported	30	Not reported	Mixed	2
Blome-Eberwein (2012)	United States	Non-commercial	16	Paediatric & adult	Burn	2
Blome-Eberwein (2016)	United States	Not reported	36	Adult	Not specified	2
Blome-Eberwein (2019)	United States	Non-commercial	19	Adult	Burn	2
Cai (2019)	China	Non-commercial	51	Adult	Not specified	2
Candy (2010)	Hong Kong	Not reported	17	Adult	Not specified	2
Chan (2004)	China	Non-commercial	56	Paediatric & adult	Burn	2
Chang (2014)	Taiwan	Non-commercial	60	Paediatric & adult	Surgical (cleft lip repair)	2
Cho (2014)	Korea	Non-commercial	146	Not reported	Burn	2
Deng (2019)	China	Not reported	20	Adult	Not specified	2
Deng (2021)	China	No funding	31	Adult	Not specified	2
Deng (2021)	Hong Kong and China	Non-commercial	45	Adult	Not specified	2
Dunkin (2007)	England	Non-commercial	113	Adult	Surgical (dermal scratch)	2
Elrefaie (2020)	Not specified	Not reported	22	Paediatric & adult	Not specified	2
Fabbrocini (2016)	Not specified	Not reported	20	Adult	Mixed	2
Fraccalvieri (2011)	Italy	No funding	5	Adult	Mixed	2
Fraccalvieri (2013)	Italy	Not reported	3	Paediatric & adult	Mixed	2
Gee Kee (2016)	Australia	Commercial	43	Paediatric	Burn	2
Issler-Fisher (2021)	Australia	Commercial	187	Adult	Burn	2
Joo (2020)	Korea	Non-commercial	48	Adult	Not specified	2
Lacarrubba (2008)	Not specified	Not reported	8	Paediatric & adult	Mixed	2

Lau (2005)	Hong Kong	Not reported	100	Paediatric & adult	Burn	2
Lee (2019)	United Kingdom	Non-commercial	55	Adult	Burn	2
Lee (2020)	United Kingdom	Non-commercial	55	Adult	Burn	2
Li (2013)	China	Non-commercial	7	Adult	Burn	2
Li (2020)	China	Not reported	21	Paediatric & adult	Mixed	2
Li (2021)	China	Non-commercial	165	Paediatric	Mixed	2
Li (2021)	China	Non-commercial	105	Adult	Burn	2
Li-Tsang (2006)	Not specified	Non-commercial	45	Adult	Not specified	2
Li-Tsang (2010)	China	Non-commercial	104	Paediatric & adult	Mixed	2
Mamdouh (2021)	Egypt	Not reported	40	Adult	Not specified	2
Meirte (2016)	Belgium	Non-commercial	9	Adult	Burn	2
Miletta (2021)	United States	Non-commercial	29	Paediatric & adult	Burn	2
Nedelec (2019)	Canada	Non-commercial	70	Adult	Burn	2
Nedelec (2020)	Canada	Non-commercial	51	Adult	Burn	2
Nicoletti (2015)	Italy	Not reported	27	Paediatric & adult	Surgical (scar reconstruction)	2
Niessen (1998)	The Netherlands	Commercial & Non-commercial	145	Paediatric & adult	Surgical (breast reduction)	2
Reinholz (2020)	Germany	No funding	25	Adult	Mixed	2
Schwaiger (2018)	Germany	No funding	15	Adult	Mixed	2
van den Kerckhove (2005)	Belgium	Not reported	60	Adult	Burn	2
van der Veer (2010)	The Netherlands	Non-commercial	44	Adult	Surgical (cardiothoracic surgery)	2
Wang (2009)	China	Non-commercial	22	Adult	Burn	2
Wiseman (2020, 2021)	Australia	Commercial & Non-commercial	153	Paediatric	Burn	2
Xuan (2021)	Not specified	Not reported	72	Not reported	Not specified	2
Yim (2010)	Korea	No funding	31	Paediatric & adult	Burn	2
Zadkowski (2016)	Not specified	Not reported	47	Paediatric	Burn	2
Avetikov (2018)	Not specified	Not reported	50	Paediatric & adult	Not specified	3

Chae (2016)	Korea	Non-commercial	23	Adult	Not specified	3
Cheng (2001)	Hong Kong	Not reported	58	Paediatric	Burn	3
Danin (2012)	France	Not reported	22	Paediatric & adult	Burn	3
Fong (1997)	Not specified	Not reported	16	Paediatric & adult	Burn	3
Gankande (2014)	Australia	Non-commercial	30	Adult	Burn	3
Ge (2022)	China	Not reported	21	Paediatric & adult	Mixed	3
Guo (2020)	China	Non-commercial	87	Paediatric & adult	Not specified	3
Huang (2017)	Taiwan	Not reported	1	Adult	Burn	3
Huang (2020)	China	Non-commercial	43	Adult	Not specified	3
Huang (2021)	Taiwan	Not reported	5	Adult	Burn	3
Issler-Fisher (2017)	Australia	No funding	47	Paediatric & adult	Burn	3
Issler-Fisher (2020)	Australia	No funding	78	Adult	Burn	3
Katz (1985)	United States	Not reported	4	Not reported	Burn	3
Kemp Bohan (2021)	United States	No funding	21	Not reported	Burn	3
Kim (2018)	Not specified	Not reported	148	Not reported	Burn	3
Li (2018)	China	Non-commercial	34	Adult	Burn	3
Li-Tsang (2005)	China	Non-commercial	101	Adult	Surgical (orthopaedic surgery)	3
Lobos (2017)	Not specified	Not reported	35	Paediatric & adult	Not specified	3
Nedelec (2008)	Canada	Non-commercial	32	Adult	Burn	3
Nedelec (2014)	Not specified	Non-commercial	46	Adult	Burn	3
Reinholz (2016)	Not specified	Commercial	8	Adult	Not specified	3
Simons (2017)	Australia	Non-commercial	49	Paediatric	Burn	3
Soykan (2014)	The Netherlands	Non-commercial	87	Adult	Surgical (cardiothoracic surgery)	3
Timar-Banu (2011)	Canada	Non-commercial	30	Adult	Mixed	3
Ud-Din (2019)	United Kingdom	Non-commercial	62	Adult	Not specified	3
van den Kerckhove (2003)	Not specified	Not reported	6	Adult	Burn	3

Wang (2010)	Australia	Commercial & Non-commercial	21	Paediatric	Burn	3
Wood (1996)	Not specified	Not reported	1	Paediatric	Burn	3
Yeol Lee (2022)	Korea	Non-commercial	16	Adult	Mixed	3
Berry (1985)	Not specified	Commercial	16	Paediatric & adult	Burn	4
Engrav (2010)	Not specified	Commercial & Non-commercial	67	Paediatric & adult	Burn	4
Abstracts						
Agabalyan (2016)	Not specified	Non-commercial	10	Not reported	Burn	2
Bajouri (2018)	Not specified	Not reported	20	Not reported	Burn	2
Blome-Eberwein (2011, 2012)	Not specified	Not reported	16	Paediatric & adult	Mixed	2
Blome-Eberwein (2014)	Not specified	Not reported	66	Not reported	Burn	2
Cho (2012)	Not specified	Not reported	60	Paediatric & adult	Burn	2
Comstock (2018)	Not specified	Not reported	1	Adult	Burn	2
Cooper (2021)	Not specified	Not reported	25	Not reported	Burn	2
El-Zawhary (2007)	Not specified	Not reported	57	Not reported	Mixed	2
Jacobs (2016)	Not specified	Not reported	6	Paediatric & adult	Burn	2
Jang (2009)	Not specified	Not reported	20	Not reported	Not specified	2
Kim (2009)	Not specified	Not reported	5	Paediatric & adult	Burn	2
Li-Tsang (2010)	Not specified	Not reported	45	Not reported	Not specified	2
Li-Tsang (2011)	Not specified	Not reported	4	Not reported	Not specified	2
Maari (2017)	Not specified	Non-commercial	12	Not reported	Not specified	2
Moortgat (2020)	Not specified	Not reported	10	Not reported	Burn	2
Nedelec (2018)	Not specified	Not reported	60	Not reported	Burn	2
Peters (2018)	Not specified	Not reported	5	Not reported	Burn	2
Siwy (2016)	Not specified	Non-commercial	15	Not reported	Burn	2
Tu (2014)	Not specified	Not reported	59	Not reported	Not specified	2
Ud-Din (2017)	Not specified	Not reported	20	Not reported	Surgical (tissue biopsies)	2
Anthonissen (2015)	Not specified	Not reported	N.R.	Not reported	Burn	3
Bezugly (2014)	Not specified	Not reported	103	Not reported	Mixed	3

Bezugly (2019)	Not specified	Not reported	438	Not reported	Not specified	3
Blome-Eberwein (2012)	Not specified	Not reported	19	Adult	Burn	3
Du (2006)	Not specified	Not reported	1	Adult	Burn	3
Edgear-Lacoursière (2022)	Canada	Not reported	44	Not reported	Burn	3
George (2019)	Not specified	Not reported	11	Not reported	Burn	3
Li (2016)	Not specified	Not reported	34	Not reported	Burn	3
Seo (2011)	Korea	Not reported	48	Not reported	Burn	3
Timina (2013)	Not specified	Not reported	49	Paediatric & adult	Not specified	3
Ud-Din (2017)	Not specified	Not reported	20	Not reported	Surgical (tissue biopsies)	3
Ud-Din (2018)	Not specified	Not reported	62	Not reported	Surgical (tissue biopsies)	3
Zuccaro (2019)	Canada	Not reported	13	Paediatric	Burn	3
Zuccaro (2021)	Not specified	Not reported	20	Paediatric	Burn	3
Zuccaro (2021)	Canada	Non-commercial	20	Paediatric	Burn	3
Cho (2012)	Not specified	Not reported	30	Not reported	Burn	4

Legend: Paediatric: measurement of patients under the age of 18; Adult: measurement of patients aged 18 years or older; N.R.: Not reported; Burn: scars caused by thermal, chemical or friction injury; Surgical: scars caused by surgical procedures (including biopsies); Mixed: participant scars caused by mixed trauma (e.g., burn and acne)

Footnotes: *Stage in the research to clinical practice translational pipeline, based on the Australian Government Department of Health and Aged Care[4]

Supplementary Table 3. Measurement methods used in included records.

First Author (year)	Ultrasound Type	Ultrasound Frequency (MHz)	Measurement Parameters	Scar Characteristic Measured	Scar Relocation
Journal articles					
Agabalyan (2017)	High-frequency	20	Epidermal, dermal & combined	N.R.	Not relevant – single measurement
Alsharnoubi (2018)	Midrange ultrasound	N.R.	N.R.	Fibrosis	N.R.
Alsharnoubi (2018)	Midrange ultrasound	N.R.	N.R.	Fibrosis[†]	N.R.
Alshehari (2015)	N.R.	N.R.	Maximum elevation above normal skin	N.R.	N.R.
Avetikov (2018)	B-mode	N.R.	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Berry (1985)	N.R.	N.R.	N.R.	N.R.	N.R.[‡]
Blome-Eberwein (2012)	B-mode	N.R.	Combined epidermal & dermal[§]	N.R.	N.R.[‡]
Blome-Eberwein (2016)	High-frequency	50	N.R.	Fibrosis[†]	N.R.[‡]
Blome-Eberwein (2019)	High-frequency	35	Dermal	Fibrosis, hair follicle density	N.R.
Cai (2019)	High-frequency	50	Dermal	N.R.	N.R.[‡]
Candy (2010)	B-mode	N.R.	N.R.	N.R.	Scar boundaries traced
Chae (2016)	N.R.	N.R	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Chang (2014)	N.R.	12	N.R.	N.R.	N.R.

Chan (2004)	N.R.	N.R.	N.R.	N.R.	Tracing
Cheng (2001)	B-mode	5-10	Combined epidermal & dermal	N.R.	Tracing & cutting out paper Photographs
Cho (2014)	High-frequency	7.5	N.R.	N.R.	N.R.
Danin (2012)	B-mode	20	Epidermal & dermal	N.R.	N.R.
Deng (2019)	N.R.	N.R.	N.R.	N.R.	N.R.
Deng (2021)	Colour Doppler	4-15	Dermal	Fibrosis[†]	N.R.
Deng (2021)	B-mode	8-12	Epidermal & dermal	Fibrosis[†]	Photographs
Dunkin (2007)	High-frequency	N.R.	N.R.	Fibrosis & oedema[†]	Measurements taken at set linear distances along scar
Elrefaie (2020)	High-frequency	13	N.R.	Fibrosis & oedema[†]	N.R[‡]
Engrav (2010)	N.R.	N.R.	N.R.	N.R.	N.R.
Fabbrocini (2016)	N.R.	N.R.	N.R.	Fibrosis & oedema[†]	N.R[‡]
Fong (1997)	B-mode	7.5	N.R.	Fibrosis[†]	Tracing
Fraccalvieri (2013)	High-frequency	7-10 & 10-13	N.R.	Fibrosis & oedema[†]	N.R.
Fraccalvieri (2011)	High-frequency	10-13	Combined epidermal & dermal	Fibrosis[†]	N.R.
Gankande (2014)	High-frequency	20	Combined epidermal & dermal	N.R.	Scar marked & photographed
Ge (2022)	N.R.	N.R.	N.R.	N.R.	N.R.
Gee Kee (2016)	B-mode	8-18	Combined epidermal & dermal	N.R.	Transducer in centre of original burn site where no scar present
Guo (2020)	N.R.	2-15 & 4-15	Combined epidermal & dermal[c]	Fibrosis[†]	Thickest site on peripheral regions
Huang (2017)	N.R.	N.R.	Combined epidermal & dermal	N.R.	Marked & linear measurements from bony landmarks

Huang (2021)	B-mode	5-12	N.R.	Oedema†	Not relevant – single measurement
Huang (2020)	B-mode	5-12	Combined epidermal & dermal	N.R.	N.R.
Issler-Fisher (2021)	N.R.	N.R.	N.R.	N.R.	Photograph & measurement of thickest area
Issler-Fisher (2020)	N.R.	N.R.	N.R.	N.R.	N.R.
Issler-Fisher (2017)	N.R.	N.R.	N.R.	Fibrosis†	Scar mapped with drawing Thickest area measured
Joo (2020)	N.R.	N.R.	N.R.	Fibrosis†	N.R.
Katz (1985)	B-mode	10	Combined epidermal & dermal	N.R.	N.R.
Kemp Bohan (2021)	High-frequency	12	N.R.	Fibrosis†	Tracing – thickest area & adjacent landmarks marked
Kim (2018)	N.R.	22	Combined epidermal & dermal	N.R.	Not relevant – single measurement
Lacarrubba (2008)	B-mode	20	Combined epidermal & dermal	N.R.	N.R.
Lau (2005)	Tissue Ultrasound Palpation System	5 (burn) & 10 (surgical)	N.R.	N.R.	Tracing – most severe/prominent site
Lee (2020)	High-frequency	20	Combined epidermal & dermal	Fibrosis†	Not relevant – single measurement
Lee (2019)	High-frequency	20	Combined epidermal & dermal	Fibrosis†	Marked with pen
Li (2013)	High-frequency	12	Combined epidermal & dermal	Fibrosis†	Tracing
Li (2020)	N.R.	10	N.R.	Fibrosis†	N.R.
Li (2021)	High-frequency	20	N.R.	N.R.	Thickest area
Li (2021)	High-frequency	20	N.R.§	Fibrosis†	Thickest area
Li (2018)	N.R.	N.R.	Combined epidermal & dermal	N.R.	N.R.
Li-Tsang (2005)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2006)	B-mode	N.R.	N.R.	N.R.	N.R‡

Li-Tsang (2010)	B-mode	N.R.	N.R.	Fibrosis[†]	N.R.
Lobos (2017)	B-mode & colour Doppler	18	N.R.	Fibrosis[†]	Not relevant – single measurement
Mamdouh (2021)	High-frequency	N.R.	Combined epidermal & dermal[§]	Fibrosis[†]	N.R.
Meirte (2016)	High-frequency	22	Dermal	Fibrosis & oedema[†]	Marked with surgical pen, including boundaries of probe. Photograph of body position & probe location
Miletta (2021)	N.R.	50	N.R.	Fibrosis[†]	Tracing – worst scar
Nedelec (2014)	High-frequency	20	Combined epidermal & dermal	N.R.	Tracing including notable landmarks. Measurement site circled. Photograph
Nedelec (2008)	High-frequency	20	Combined epidermal & dermal	N.R.	Tracing including notable landmarks. Measurement site circled. Photograph
Nedelec (2019)	High-frequency	20	Combined epidermal & dermal	Fibrosis & oedema[†]	Tracing. Hole cut over measurement area
Nedelec (2020)	High-frequency	20	Combined epidermal & dermal	N.R.	Photograph
Nicoletti (2015)	N.R.	22	Epidermis to fascia	N.R.	N.R.
Niessen (1998)	B-mode	N.R.	N.R.	Fibrosis & oedema[†]	3cm border marked with tape – measurements lateral
Reinholz (2020)	B-mode	11	Combined epidermal & dermal	Fibrosis & oedema[†]	N.R.
Reinholz (2016)	B-mode	11	Combined epidermal & dermal[§]	Fibrosis & oedema[†]	N.R.
Schwaiger (2018)	B-mode	11	N.R.	Fibrosis & oedema[†]	N.R.
Simons (2017)	B-mode	8-18	Combined epidermal & dermal	N.R.	Tracing – scar & anatomical landmarks

Soykan (2014)	N.R.	3-9	N.R.	Fibrosis†	N.R.
Timar-Banu (2001)	High-frequency	20	Combined epidermal & dermal	Fibrosis†	N.R.
Ud-Din (2019)	High-frequency	50	Combined epidermal & dermal	Fibrosis	Defined anatomical location
van den Kerckhove (2003)	High-frequency	20	Combined epidermal & dermal	N.R.	Test sites marked. Thermoplastic splints created with space for transducer
van den Kerckhove (2005)	High-frequency	20	Combined epidermal & dermal	N.R.	Test site boundaries marked & traced
van der Veer (2010)	N.R.	7.5	N.R.	Fibrosis†	Standardised linear measurement points
Wang (2009)	High-frequency	N.R.	N.R.	Fibrosis†	N.R.
Wang (2010)	B-mode	N.R.	Combined epidermal & dermal	N.R.	Tracing – scar & anatomical landmarks
Wiseman (2020, 2021)	B-mode	N.R.	Combined epidermal & dermal	Fibrosis†	Centrally site of interest
Wood (1996)	B-mode	7 & 10	N.R.	N.R.	Transducer affixed to tracking arm
Xuan (2021)	High-frequency	20	N.R.	Fibrosis†	N.R.
Yeol Lee (2022)	B-mode	7-16	N.R.	N.R.	N.R.
Yim (2010)	High-frequency	12	N.R.	N.R.	N.R.
Zadkowski (2016)	B-mode	N.R.	Combined epidermal & dermal	N.R.	N.R.
Abstracts					
Agabalyan (2016)	N.R.	20	Epidermal, dermal & combined	N.R.	N.R.
Anthonissen (2015)	N.R.	22	Epidermal & dermal	N.R.	N.R.
Bajouri (2018)	High-frequency	N.R.	Epidermal & dermal	N.R.	N.R.

Bezugly (2019)	High-frequency	22, 33 & 75	Epidermal & dermal	N.R.	N.R.
Bezugly (2014)	High-frequency	33 & 75	Epidermal & dermal	N.R.	N.R.
Blome-Eberwein (2011, 2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Blome-Eberwein (2012)	High-frequency	N.R.	N.R.	Fibrosis	N.R.
Blome-Eberwein (2014)	High-frequency	N.R.	N.R.	N.R.	N.R.
Cho (2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Cho (2012)	N.R.	N.R.	N.R.	N.R.	N.R.
Comstock (2018)	N.R.	N.R.	N.R.	N.R.	N.R.
Cooper (2021)	N.R.	N.R.	N.R.	N.R.	N.R.
Du (2006)	B-mode	15	N.R.	N.R.	N.R.
Edgar-Lacoursière (2022)	N.R.	N.R.	N.R.	N.R.	N.R.
El-Zawhary (2007)	N.R.	N.R.	N.R.	N.R.	N.R.
George (2019)	N.R.	N.R.	N.R.	N.R.	N.R.
Jacobs (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Jang (2009)	N.R.	N.R.	N.R.	N.R.	N.R.
Kim (2009)	N.R.	N.R.	N.R.	N.R.	N.R.
Li (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2011)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Li-Tsang (2010)	Tissue Ultrasound Palpation System	N.R.	N.R.	N.R.	N.R.
Maari (2017)	N.R.	N.R.	N.R.	N.R.	N.R.

Moortgat (2020)	High-frequency	N.R.	Dermal	N.R.	N.R.
Nedelec (2018)	N.R.	N.R.	N.R.	N.R.	N.R.
Peters (2018)	High-frequency	22	N.R.	N.R.	N.R.
Seo (2011)	N.R.	7.5	N.R.	N.R.	Thickest point
Siwy (2016)	N.R.	N.R.	N.R.	N.R.	N.R.
Timina (2013)	N.R.	20-40	N.R.	N.R.	N.R.
Tu (2014)	High-frequency ultrasound biomicroscopy	N.R.	N.R.	N.R.	N.R.
Ud-Din (2017)	N.R.	N.R.	N.R.	N.R.	N.R.
Ud-Din (2017)	High-frequency	50	N.R.	N.R.	N.R.
Ud-Din (2018)	High-frequency	N.R.	N.R.	Fibrosis[†]	N.R.
Zuccaro (2021)	N.R.	N.R.	N.R.	N.R.	N.R.
Zuccaro (2019)	B-mode	N.R.	N.R.	N.R.	N.R.
Zuccaro (2021)	B-mode	6-18	Combined epidermal & dermal	N.R.	Scar outlined & photographed

Legend: Scar relocation: Methods used by assessors to relocate the measured scar for sequential measurements; B-mode: brightness-mode ultrasound (< 20 MHz); High-frequency: high-frequency B-mode ultrasound (> 20 MHz); N.R.: Not reported

Footnotes: [†]Indirect reference made in record (e.g. in introduction or discussion); [‡]Photographs taken of the scar but not specified whether used for relocation; [§]Not stated in methods, so images provided in record used by authors of this review to provide subjective judgement

Supplementary Table 4. Additional measurement methods used alongside ultrasound in included studies

First author (year)	Objective measurement methods	Clinician-based rating scale	PROM
Journal articles			
Agabalyan (2017)	Histology	-	-
Alsharnoubi (2018)	Laser Doppler perfusion	VSS	-
Alsharnoubi (2018)	Laser Doppler perfusion	VSS	-
Alshehari (2015)	-	VSS	-
Avetikov (2018)	-	-	-
Berry (1985)	Transcutaneous oxygen measurement	Scar redness and hypertrophy rating scale (0-5 Likert scale)	Scar redness and hypertrophy rating scale (0-5 Likert scale)
Blome-Eberwein (2012)	Doppler flowmeter – vascularity Cutometer – pliability Semmes-Weinstein monofilament Aesthesiometer testing set – sensation	VSS POSAS-O	POSAS-P
Blome-Eberwein (2016)	Cutometer – pliability Dermaspectrometer – colour Semmes-Weinstein Aesthesiometer Monofilament Testing Set – sensation	VSS POSAS-O	POSAS-P
Blome-Eberwein (2019)	-	VSS	-
Cai (2019)	-	Clinical evaluation	-
Candy (2010)	Spectrocolorimeter – colour	VSS	-
Chae (2016)	Spectrophotometer – pigmentation	VSS POSAS-O	POSAS-P
Chang (2014)	-	VSS Photographic evaluation (0-10 VAS)	-
Chan (2004)	Cutometer – viscoelasticity Spectrophotometer – pigmentation	-	-
Cheng (2001)	-	VSS	-
Cho (2014)	Mexameter – colour	Treatment efficacy (0-10 VAS)	Itching scale (0-4 Likert scale)

	Tewameter – trans-epidermal water loss Sebumeter – sebum Cutometer – elasticity		
Danin (2012)	Cutometer – elasticity	VSS	-
Deng (2019)	DermaLab Combo – colour Dermoscopy – vascularity	POSAS-O	-
Deng (2021)	-	VSS	-
Deng (2021)	Doppler – blood perfusion Dermlite Foto IIPro – erythema	POSAS-O	POSAS-P
Dunkin (2007)	-	-	-
Elrefaie (2020)	Ultrasound – echogenicity, compressibility & vascularity	VSS	-
Engrav (2010)	Durometer – hardness Chromameter – colour	Clinical appearance based on photographs	-
Fabbrocini (2016)	-	mVSS (vascularity, pigmentation, pliability)	-
Fong (1997)	Cutometer – elasticity	Clinical rating – colour change, consistent itch, hypersensitivity, blistering	-
Fraccalvieri (2013)	Colour power Doppler – vascularisation	VSS Visual analogue scale – pain and itch	
Fraccalvieri (2011)	Histology Echocontrastography – neovascularisation	-	-
Gankande (2014)	DermLab combo – erythema & elasticity	mVSS (some participants)	-
Ge (2022)	-	POSAS-O Subjective reports on patient range of movement	POSAS-P
Gee Kee (2016)	3D photography – thickness	POSAS-O	POSAS-P
Guo (2020)	Ultrasound – blood flow grade Shear wave elastography – scar stiffness	-	-

Huang (2017)	-	-	-
Huang (2021)	-	-	-
Huang (2020)	Shear wave elastography – scar stiffness	-	-
Issler-Fisher (2021)	-	VSS POSAS-O	POSAS-P
Issler-Fisher (2020)	-	VSS POSAS-O	POSAS-P Patient pain & itch scales
Issler-Fisher (2017)	-	VSS POSAS-O	POSAS-P Patient pain, itch & quality of life rating scales
Joo (2020)	-	VSS	Pain severity (0-10 VAS)
Katz (1985)	Cicatrometer – firmness	-	-
Kemp Bohan (2021)	-	-	-
Kim (2018)	-	-	-
Lacarrubba (2008)	-	Clinical evaluation of lesion size	-
Lau (2005)	-	VSS	-
Lee (2020)	-	mVSS (height, pliability, vascularity, pigmentation) POSAS-O	POSAS-P
Lee (2019)	-	mVSS (height, pliability, vascularity, pigmentation) POSAS-O	POSAS-P
Li (2013)	Micrometer – tissue thickness Force/torque sensor – load applied to scar	-	-
Li (2020)	Cutometer – elasticity Mexameter – colour PeriCam PSI system and mexameter – blood supply	VSS	Quality of life questionnaire
Li (2021)	Laser Doppler flowmetry – perfusion	VSS	-
Li (2018)	Spectrocolourimeter – scar colour	VSS	Pain & itch (0-10 VAS)
Li (2021)	-	VSS	Treatment satisfaction
Li-Tsang (2005)	Spectrocolourimeter – scar colour	VSS	Pain & itch (VAS scale not specified)
Li-Tsang (2006)	Spectrocolorimeter – colour	VSS	Pain & itch (VAS)

Li-Tsang (2010)	Spectrocolorimeter – colour	VSS (pliability)	Pain & itch (10-point VAS)
Lobos (2017)	-	Modified Seattle Scar Scale Clinical opinion	-
Mamdouh (2021)	-	VSS	Patient satisfaction (VAS)
Meirte (2016)	-	-	-
Miletta (2021)	Colourmeter – scar colour Dermal torque meter – scar compliance	Unclear, likely POSAS-O	Unclear, likely POSAS-P Short Form 36 Quality of Life Survey
Nedelec (2014)	Cutometer – elasticity Mexameter – colour	-	-
Nedelec (2008)	Cutometer – elasticity Mexameter – colour	mVSS	-
Nedelec (2019)	Cutometer – elasticity Mexameter – colour	-	-
Nedelec (2020)	Cutometer – elasticity Mexameter – colour	-	Pain & itch (10cm line VAS)
Nicoletti (2015)	-	-	-
Niessen (1998)	Histology	-	-
Reinholz (2020)	3D topographic imaging device	POSAS-O	Dermatology Quality of Life Index POSAS-P
Reinholz (2016)	Optical coherence tomography – thickness	POSAS-O	Dermatology Quality of Life Index POSAS-P
Schwaiger (2018)	3D topographic imaging device	-	-
Simons (2017)	3D camera – scar height	POSAS-O	-
Soykan (2014)	Slide calliper – dimensions	POSAS-O	POSAS-P
Timar-Banu (2001)	Metric ruler – dimensions	Validated 3-point scoring system for redness, hardness, itching & pain	-
Ud-Din (2019)	Optical coherence tomography – thickness Histology	-	-
van den Kerckhove (2005)	Chromameter – erythema	-	-
van der Veer (2010)	Slide calliper – dimensions	-	-
Wang (2009)	Histology	-	-
Wang (2010)	-	-	-

Wiseman (2020, 2021)	-	POSAS-O	POSAS-P Numeric rating scale for itch Toronto Paediatric Itch Scale CH-9D BBSIP
Wood (1996)	-	VSS	-
Xuan (2021)	Histology	-	-
Yeol Lee (2022)	Cutometer – elasticity Elastography	mVSS	-
Yim (2010)	Cutometer – elasticity Tewameter – trans-epidermal water loss Mexameter – colour	-	-
Zadkowski (2016)	-	VSS	-
Abstracts			
Agabalyan (2016)	Histology	-	-
Bajouri (2018)	-	VSS	-
Bezugly (2019)	Clinical or histopathological diagnosis	-	-
Bezugly (2014)	-	-	-
Blome-Eberwein (2011, 2012)	Doppler vascularity, elasticity and sensation	VSS	Pain and itching scale (0-10 Likert scale)
Blome-Eberwein (2012)	-	-	-
Blome-Eberwein (2014)	Doppler flowmeter – vascularity Cutometer – pliability Semmes-Weinstein monofilament aesthesiometer testing set – sensation	VSS	POSAS-P
Cho (2012)	-	VSS	-
Cho (2012)	CK-MPA Multi-Probe adaptor – pigmentation, erythema and trans-epidermal water loss Cutometer – elasticity	-	-
Comstock (2018)	Computer-based tools – Thickness & pliability	Unclear, likely POSAS-O	Unclear, likely POSAS-P

Cooper (2021)	Colorimeter – pigmentation	Unclear, likely POSAS-O	Unclear, likely POSAS-P
Du (2006)	-	-	-
Edgar-Lacoursière (2022)	Cutometer – elasticity Mexameter – colour	-	-
El-Zawhary (2007)	Histology	-	-
George (2019)	-	-	-
Jacobs (2016)	Cutometer – pliability Colorimeter – colour	POSAS-O	-
Jang (2009)	Mexameter – pigmentation Tewameter – trans-epidermal water loss Sebumeter – sebum Cutometer – elasticity Laser Doppler – perfusion	-	-
Kim (2009)	Histology	VSS	-
Li (2016)	Spectrocolourimeter – scar colour	VSS	Patient report of pain & itch
Li-Tsang (2011)	-	VSS (thickness, pliability and pigmentation)	-
Li-Tsang (2010)	Histology Spectrocolourimeter – scar colour	VSS	Self-report questionnaire
Maari (2017)	Cutometer – elasticity Mexameter – pigmentation	-	-
Moortgat (2020)	Cutometer – elasticity Chromameter – colour Tewameter – trans-epidermal water loss Corneometer – hydration	Unclear, likely POSAS-O	Unclear, likely POSAS-P
Nedelec (2018)	Cutometer – elasticity Mexameter – colour	-	-
Peters (2018)	Cutometer – elasticity Colourimeter – colour	POSAS-O	POSAS-P
Seo 2011	Cutometer – elasticity		
Siwy (2016)	Colourimeter – colour Torque meter – pliability & elasticity	-	SF-36 Quality of Life Measurement POSAS-P
Timina (2013)	-	-	-

Tu (2014)	-	VSS	-
Ud-Din (2017)	Laser perfusion imaging Optical coherence tomography – thickness Histology	-	-
Ud-Din (2017)	Optical coherence tomography – thickness	-	-
Ud-Din (2018)	Optical coherence tomography – thickness Histology	-	-
Zuccaro (2021)	Multi-parameter skin analysis device	VSS Unclear, likely POSAS-O	Unclear, likely POSAS-P
Zuccaro (2019)	Acoustic radiation force impulse ultrasound elastography	-	-
Zuccaro (2021)	Acoustic radiation force impulse – stiffness DermLab Combo elasticity probe – elasticity DermLab Combo colour probe – colour	VSS POSAS-O (did not include surface area and relief subscales)	POSAS-P

Legend: (m)VSS: (Modified) Vancouver Scar Scale; POSAS: Patient and Observer Scar Assessment Scale (POSAS-O: POSAS observer scale; POSAS-P: POSAS patient scale); VAS: Visual Analogue Scale; CHU-9D: Child Health Utility-9D; BBSIP: Brisbane Burn Scar Impact Profile

Supplementary Table 5: Reliability of ultrasound methods reported in each included study

First Author (year)	Reliability Test & Measurement Error	Reliability & Measurement Error Test Statistics & Details
Inter-rater reliability		
Anthonissen (2015)	ICC; SEM	Epidermal – 0.297; 0.02mm Dermal – 0.991; 0.13mm
Chang (2014)	Pearson correlation	R=0.90, p<0.001
Dunkin (2007)	N.R.	N.R.
Fong (1997)	ICC	0.93, p=0.146
Gankande (2014)	ICC (95% CI)	Individual site: **Rater 1 vs rater 2** 'Best scar' – 0.95 (0.92, 0.96) 'Worst scar' – 0.95 (0.91, 0.97) 'Normal skin' – 0.94 (0.91, 0.96) **Rater 1 vs rater 3:** 'Best scar' – 0.86 (0.78, 0.91) 'Worst scar' – 0.91 (0.85, 0.95) 'Normal skin' – 0.92 (0.88, 0.95) **Rater 2 vs rater 3:** 'Best scar' – 0.93 (0.89, 0.95) 'Worst scar' – 0.96 (0.92, 0.97) 'Normal skin' – 0.95 (0.92, 0.97) Average site: **Rater 1 vs rater 2** 'Best scar' – 0.97 (0.94, 0.99) 'Worst scar' – 0.98 (0.96, 0.99) 'Normal skin' – 0.97 (0.93, 0.98) **Rater 1 vs rater 3** 'Best scar' – 0.90 (0.77, 0.95) 'Worst scar' – 0.97 (0.91, 0.98) 'Normal skin' – 0.96 (0.92, 0.98) **Rater 2 vs rater 2** 'Best scar' – 0.95 (0.88, 0.98) 'Worst scar' – 0.98 (0.94, 0.99) 'Normal skin' – 0.98 (0.97, 0.99)
Lau (2005)	ICC	0.84, p<0.01
Lee (2020)	ICC	"Acceptable to high"
Lee (2019)	ICC (95% CI); SEM	Scar: Single: 0.957 (0.934-0.973) Average: 0.985 (0.977-0.991) SEM: 0.10 mm Unscarred skin: Single: 0.967 (0.949-0.980) Average: 0.989 (0.982-0.993) SEM: 0.04 mm
Nedelec (2008)	ICC (95% CI)	Most severe scar: 0.90 (0.84-0.95) Less severe scar: 0.91 (0.85-0.95) Donor site: 0.89 (0.82-0.94) Normal skin: 0.85 (0.75-0.92)
Seo (2011)	N.R.	"High"
Simons (2017)	ICC (95% CI); SEM	Scar: 0.82 (0.7-0.89); 0.05 cm Normal skin: 0.33 (0.08-0.54); 0.03 cm
Van Den Kerckhove (2003)	ICC (95% CI); SEM	One day: 0.88 (0.81-0.95); 0.29 mm

		Day-to-day: 0.94 (0.90-0.98); 0.21mm
Intra-rater reliability		
Anthonissen (2015)	ICC; SEM	Epidermal – 0.809; 0.01mm Dermal – 0.991; 0.13mm
Gankande (2014)	ICC (95% CI)	'Best scar' – 0.97 (0.89, 0.94) 'Worst scar' – 0.92 (0.88, 0.95) 'Normal skin' – 0.86 (0.81, 0.89)
Gee Kee (2016)	N.R.	N.R.
Lau (2005)	ICC	Intra-rater: 0.98, p<0.01
Lee (2019)	ICC (95% CI)	Scar: Single: 0.951 (0.871-0.987) Average: 0.983 (0.953-0.966) SEM: 0.10 mm Unscarred skin: Single: 0.948 (0.881-0.976) Average: 0.982 (0.954-0.993) SEM: 0.04 mm
Li (2013)	ICC	0.89
Seo (2011)	N.R.	"High"
Simons (2017)	ICC (95% CI); SEM	Scar: 0.95 (0.91-0.97); 0.02 cm Normal skin: 0.61 (0.41-0.75); 0.02 cm
Van Den Kerckhove (2003)	ICC (95% CI); SEM	0.98 (0.97-0.99); 0.11mm
Wang (2010)	SE	Peak: 0.032 3 months: 0.018 6 months: 0.399 9 months: 0.353

Abbreviations used in tables: N.R.: Not reported; ICC: Intraclass Correlation Coefficient; 95% CI: 95% Confidence Interval; SEM: Standard Error of Measurement; SE: Standard Error

Summary of findings for measurement error:

The reported inter-rater SEM measurements for the combined (i.e., epidermal and dermal) thickness measurement of scars was reported in two records as 0.11 mm[5] and 0.5 mm.[6] The inter-rater SEM for the combined thickness measurement of unscarred skin was also calculated in one record (SEM = 0.3 mm).[6] The inter-rater SEM was calculated in one record for the measurement of epidermal (SEM = 0.02 mm) and dermal (0.13) measurements[7], and one record reported only the dermal SEM for scar thickness (SEM = 0.1 mm) and unscarred skin (0.04 mm).[8] The intra-rater SEM for the combined thickness measurement of scarred skin ranged from 0.18 mm to 0.52 mm, and was measured at 0.2 mm for unscarred skin in one record.[6] One record reported the intra-rater SEM for epidermal (0.01 mm) and dermal (0.12 mm),[7] and one record reported the intra-rater SEM for dermal scar (0.1 mm) and unscarred skin (0.04).[8]

Supplementary Table 6. Methodological considerations for researchers and/or clinicians undertaking measurement of scar thickness using ultrasound.

Consideration	Details & examples of considerations	Publications in our review addressing the consideration	Details reported in included review records
Preventing skin compression during measurement	Using standoff methods (e.g., ultrasound gel, water bath) to prevent transducer touching the skin	[6,9-13]	- Use of ultrasound gel to prevent contact between ultrasound transducer and skin surface to minimise compression applied by direct application of transducer [6,9-12] - Silicone pad placed underneath transducer [13]
	Application of minimal pressure by transducer	[14-18]	- Transducer held to maintain minimal pressure on scar [14,15,17] - Training users to apply minimal force on transducer to prevent scar or skin distortion [16,18]
	Deliberately compressing skin to quantify scar compressibility	[19-21]	- Measurement of thickness with and without compression with transducer [19,21] - Thickness measurements taken using TUPS, which uses controlled and metered compression during measurement [20]
Orienting the patient	Orienting the patient during measurement (e.g., upright, supine, prone or seated)	[8,18,22]	- Patient supine throughout measurement to allow measurement to be taken in the same position [8,18,22]
	Maintaining patient stillness during measurement	[9]	- Patients asked to hold breath during measurement of scars on the chest to allow shear-wave ultrasound [9]
Placing ultrasound transducer	Orientating ultrasound transducer [e.g., vertical (superior to inferior/cranial to caudal), horizonal (medial to lateral)]	[23]	- Direction of transducer recorded to ensure consistency [23]

	Orienting the transducer in relation to the scar (e.g., perpendicular)	9,15,17,18,22,24-26	- Transducer oriented perpendicular to the skin surface to provide optimal image [9,15,18,22,24-26]
	Measuring difficult/tight areas (e.g., axillae or other joints)	6	- Exclusion of fingers and toes in paediatric measurements due to size of measurement area and thin skin [6]
Relocating scars for longitudinal measurement	Mapping measurement area (e.g., tracing, schematic diagram)	6,12,16,18,20,22,27-32	- Scars traced using translucent paper [18,20,22,27,29,31,32] - Scars and surrounding anatomical landmarks traced using translucent paper [16] - Scar mapped on transparent paper, which was then cut out [28] - Scar mapped with drawing, no elaboration provided [30] - Scars traced using Visitrak (Smith & Nephew Medical Limited, England) [6,12]
	Photographing measurement area	24,26,33	- Assessed area marked and photograph taken in initial consultation [24,33] - Photographs of scars taken [26]
	Measuring specific scar locations (e.g., centre of scar, worst area of scar, counting transducer lengths)	6,8,9,13,19-21,23,30,33-37	- Measurement taken at standardised transducer lengths along surgically created scars of pre-specified dimensions [34] - Measurements taken at thickest/most severe point [19-21,30,33,35,37], as determined by the patient and/or clinician [8] - Transducer placed on thickest site on peripheral regions [9] - Transducer placed on area initially identified to have greatest burn depth [23]

			- Measurement area selected by the measurer with -selected area marked with tape [13] - Measurements taken at set linear distances from cranial/caudal border of linear sternal scar [36]
	Conducting linear measurements from nearby anatomical landmarks	17,38	- Linear measurements from anatomical landmark to measurement site [17] - Transducer placement mapped in 3-dimensional space using a surgical precision tracking arm [38]
Acclimatising scar to measurement conditions	Removing scar treatments prior to ultrasound measurement	8,12,20,22,24-26,28,29,39,40	- Pressure garments removed 10 minutes before measurement [28] - Pressure garments removed 15 minutes before measurement to regain original (uncompressed) scar thickness or to reduce blanching effects on measurement [20,40] - Pressure garments/gels/moisturisers removed 20 minutes before measurement [8,22,29] - Pressure garments removed 30 minutes before measurement [12,25,26,39] - Sequential measurement of scars following direct treatment with vacuum massage at 5, 30, 60 and 120 minutes to monitor effect of treatment [24]
	Acclimatising patient to room prior to measurement	5,18,22,29,41-46	- Patients rested for minimum 5 minutes before measurement [5,18,22] - Scar exposed to room conditions for 10 minutes [29] to allow equilibrium to be reached with surrounding environment [41] - Patients resting in room with constant temperature for 15 mins [42] to allow scar to stabilise [44]

			- Patients rested for 20 minutes prior to measurement [29,45] - Patients resting for 10 minutes before repeated measurements taken [43] - Patients wait in testing room holding position for 5 min before measurement to stabilise cutaneous blood flow [5] - Patients allowed to adapt in controlled room to exclude external variables [46]
	Maintaining patient position before measurement	11,13	- Patients remained supine for at least 5 minutes before measurement to avoid artefacts on Doppler imaging [13] - Patients allowed to acclimatise to room and assumed a supine position for a minimum of 10 minutes before measurements of biophysical parameters [11]
Measuring different skin layers	Measuring epidermis and/or dermis individually	7,24,37,45,47-54	- Measurement of epidermal, dermal and combined epidermal and dermal thickness to allow comparison with histological measurement [47,48] - Measurement of the epidermal and dermal thickness [45,49], combined with layer acoustic density [7] - Measurement of the epidermal, dermal and subcutaneous thickness, combined with acoustic density [50,51] - Measurement of dermal thickness as treatment thought to affect/target the dermis [24,37,52-54]
	Measuring both epidermis/dermis combined (no	5,6,8,11,12,15,17,18,22,23,26,28,35,40,55-68	- Combined epidermal and dermal thickness measurement to provide information on the full thickness of the scar [5,6,8,11,12,15,17,18,22,23,26,28,35,40,55-68]

	individual measurement)		
Measurement objective	Measuring fibrosis/oedema/hair follicles	8,10,11,13,14,16,17,24,25,29-32,34,36,37,45,54,58,60,61,63,64,69-82	- Measurement of fibrosis or collagen architecture [8,11,17,24,29-32,34,36,37,45,54,58,61,63,64,69,70,72-74,77-79,82] - Measurement of inflammation/oedema [14] - Quantification of the sub epidermal low echogenic band, indicating oedema [60] - Measurement of both fibrosis and oedema [10,13,16,25,58,71,75,76,80,81] - Measurement of the presence and density of hair follicles to differentiate scarred and unscarred skin[54]
Factors influencing scar site measurement	Measuring contralateral skin/control scar	9,14,15,23,29,30,52,55-58,83-88 6,8,12,18,22,25,38,43,54,59-61,66,89,90 39,40,45,79,81,82	- Measurement of additional, non-scarred subjects [55,79] - Measurement of unscarred/unaffected skin on same subject as scar measurement contralaterally or at anatomically similar location to provide normative measurements for skin thickness [6,8,9,12,14,15,18,22,23,29,30,38-40,43,45,52,54,56-61,66,81,85-90] - Measurement of both untreated scar and unaffected skin [82-84] - Measurement of a control scar subjected to care as usual treatment on the same individual [25]
	Measuring open wounds or sores in the scar	6	- Use of flexible transparent plastic wrap placed over the measurement area to prevent contact between ultrasound gel and transducer with the open wound/sore [6]
	Operator training and/or experience	6,8,12,14,16,18,20,24,27-29,31,39,40,58,61,66,72,73,87,91-93	- Trained outcome assessor [6,13,16,18,27,72] - Measurements taken by radiologist/sonographer [28,66,73,92]

		- Assessors with burn experience [87,93] - Ultrasound located in department of radiology [91] - Measurements conducted by trained therapist/doctor under guidance of experienced radiologist [12,14,29,39] - Measurements conducted by trained clinicians who use device regularly and received training by company representative of devices [8,61] - Device-specific training provided: 1 week [20]; 3 sessions of 3 hours for 3 weeks, plus 10 independent assessments of scars using study protocol [40]; training provided over 3 months [31]; physical therapist trained in ultrasound application [24]
Number of measurements per scar	5,6,8,9,11,12,20,23,25,26,31,34,37,40,44,45,47,52,54,57,60,61,66,68,79,85,92,94	- 3 ultrasound images taken from each patient [9,11,26,31,37,44,45,47,52,54,57,60,79,85] - Clearest of 3 measurements used [12] - 3 measurements in 3 locations across scar used. Individual and average measurements reported [40] - Measurements performed in duplicate [34,94] - Measurements taken at different points of the scar, thickest used for analysis [92] - 5 measurements of each site [6,23] - 9 measurements taken, removal of maximum and minimum, 7 measurements used for average [20] - Measurements taken by 3 assessors at 3 different time points during day [8,61] - Measurement of 2 sites on the same scar [25] - Single ultrasound image taken for analysis [68]

Use of additional measurement tools as well as ultrasound measurements	Using additional objective assessment instruments (e.g., histology, colour Doppler ultrasound, cutometer, colourimeter)	6,9-11,13,15,17,18,21-23,25-27,29,31,32,35,36,40-48,50,53,56-59,66,68-70,75-80,82-84,86-92,95-111	- Histology/immunohistochemistry [13,17,47,48,50,58,78,79,88,100,103,108,110] - Blood flow and blood perfusion measurement using laser Doppler perfusion imaging, flowmetry or PeriCam, and scar colour and micro-vessel percentage using dermoscopyolour and micro-vessel percentage. [35,69,70,83,84,86,87,92,99,101,108] - Oximeter [41] - Infra-red camera [41] - Measurement of scar stiffness or pliability/elasticity using elastography or cutometer [9,15,18,21,22,25-27,29,43,46,53,57,66,82-84,86,89,90,96,98,99,101,104-106] - Measurement of sensation using Semmes-Weinstein filaments [82-84,86] - Measurement of scar colour (including pigmentation and erythema) using spectrophotometer, colourimeter, chromameter, mexameter or Dermlite Foto IIPro [18,22,25-27,32,42,44-46,53,56,66,68,80,82,87,90,91,96-99,101-107,111] - Measurement of trans-epidermal water loss using Tewameter or scar hydration using Corneometer [46,53,96,99] - Measurement of sebum level using sebumeter [96,99] - Measurement of hardness using durometer [91] - Measurement of neovascularisation using echocontrastography [58] - Measurement of scar dimensions (e.g., scar height and volume) using 3D camera, 3D imaging methods, ruler or calliper [6,10,11,23,36,75,77]

		- Measurement of skin thickness using micrometer or optical coherence tomography [17,31,59,76,108-110] - Measurement of scar firmness or deformation using cicatrometer, force/torque sensor (in line with ultrasound to measure load applied) or torque meter [31,32,107] - Multi-parameter skin analysis device [66] - Measurement of erythema and elasticity using probes of DermaLab Combo [40] - Multi-probe adaptor taking multiple measurements (pigmentation, erythema, trans-epidermal water loss) [96]
Using subjective assessment instruments (e.g., clinical rating scales, PROMs)	[19,20,23,28-30,33,37,40,41,44,45,49,52,56,57,61,66,67,69-72,80-84,86,87,91,92,94-98,100,111-115]	PROMs: - Measurement of scar quality using POSAS patient report [8,23,30,33,45,56,61,63,64,66,75-77,82,86,95,97,106,107,114,115] - Subjective rating scales for scar symptoms (e.g., pain, itch) or subjective scar severity ratings [26,30,41,42,53,63,64,72,80,83,84,93,102,103,111,115] - Patient quality of life questionnaires [75,76,101,107] - Measurement of generic health-related quality of life using CHU-9D [63,64] - Measurement of scar-specific health-related quality of life using BBSIP [63,64] - subjective evaluation of response to treatment/treatment satisfaction [81,116] Clinical rating scales: - Measurement of scar quality using POSAS observer report [8,23,30,33,45,53,56,61,63,64,66,75-77,82,86,87,97,98,106,114-116]

		- Measurement of physical scar characteristics using VSS or modified versions of the VSS [8,18-20,28,30,33,35,37,38,40,42-44,49,56,57,61,65,66,69-72,80-86,92-95,100-103,111-113,115,117,118] - Measurement of scar characteristics in relation to unscarred skin using Seattle Scar Scale or modified Seattle Scar Scale [73] - Subjective rating scales for scar symptoms (e.g., pain, itch) as assessed by the clinician and/or researcher and/or clinical evaluation of scar severity [11,29,41,52,57,67,73,91,92,94,96]
Determining the order of measurement	6	- Standardised order of measurement: 3D photograph, POSAS-O, then ultrasound [6] - Order of device use not specified [35,69,70,83,84,86,87,92,99,101,108]

Abbreviations: TUPS: Tissue Ultrasound Palpation System; 3D: three-dimensional; POSAS: Patient and Observer Scar Assessment Scale; CHU-9D: Child Health Utility 9D; BBSIP: Brisbane Burn Scar Impact Profile; VSS: Vancouver Scar Scale; mVSS: Modified Vancouver Scar Scale; POSAS-O: Patient and Observer Scar Assessment Scale, observer measure

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Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	3-4
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	5-7
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	7
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	7
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	8-10
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	8
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	9
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	9
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	10-11
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	10-11 and supplementary table 1
Critical appraisal of individual	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe	N/A

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
sources of evidence§		the methods used and how this information was used in any data synthesis (if appropriate).	
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	10-11
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	11-12
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	12-15
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Results section (11-46)
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Results section (11-46)
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	47-49
Limitations	20	Discuss the limitations of the scoping review process.	49-50
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	50-51
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	51

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

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