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Collaboration and knowledge generation in an 18- year quality improvement research program in Australian Indigenous primary health care: a co-authorship network analysis

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TITLE PAGE

Title

Collaboration and knowledge generation in an 18- year quality improvement research program in Australian Indigenous primary health care: a co-authorship network analysis

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Key words

Quality improvement; collaboration; research networks; social network analysis; co-authorship network analysis; evaluation; innovation platforms; partnership research

ABSTRACT

Objectives

Though multidisciplinary research networks support the practice and effectiveness of continuous quality improvement (CQI) programs, their characteristics and development are poorly understood. In this study we examine publication outputs from a research network in Australian Indigenous primary health care (PHC) to assess to what extent the research network changed over time.

Setting

Australian CQI research network in Indigenous PHC from 2002 - 2019.

Participants

Authors from peer-reviewed journal articles and books published by the network.

Design

Co-author networks across four phases of the network (2002–04; 2005–09; 2010–14; 2015–19) were constructed based on author affiliations and examined using social network analysis methods. Descriptive characteristics included organisation types, Indigenous representation, gender, student authorship and thematic research trends.

Results

We identified 128 publications written by 308 individual authors from 79 different organisations. Publications increased in number and diversity over each funding phase. During the final phase, publication outputs accelerated for organisations, students, project officers, Indigenous and female authors. Over time there was also a shift in research themes to encompass new clinical areas and social, environmental or behavioural determinants of health. Average degree (8.1), clustering (0.81) and diameter (3) indicated a well-connected network, with a core-periphery structure in each phase ($p \leq .03$) rather than a single central organisation (degree-centralisation=0.55-0.65). Academic organisations dominated the core structure in all funding phases.

Conclusion

Collaboration in publications increased with network consolidation and expansion. Increased productivity was associated with increased authorship diversity and a decentralised network, suggesting

these may be important factors in enhancing research impact and advancing the knowledge and practice of CQI in primary health care. Publication diversity and growth occurred mainly in the fourth phase, suggesting long-term relationship building among diverse partners is required to facilitate participatory research in CQI. Despite improvements, further work is needed to address inequities in female authorship and Indigenous authorship.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- A study strength was the long timeframe of 18 years of publications from an Australian quality improvement research network.

- Although co-authorship is only one indicator of collaboration, there are several advantages to relying on it as a proxy for assessing the level of research collaboration, including its verifiability, stability over time, availability of data in the public domain and ease of measurement.

- Methods such as co-authorship analysis are useful for demonstrating a pathway to research impact related to engagement, which traditionally tends to rely on the quantity of outputs rather than on the strengthening of networks and the scope of work undertaken.

- Co-authorship is only one indicator of collaboration, though it has several advantages to relying on it as a proxy for assessing research collaboration including its verifiability, stability over time, and availability in the public domain.

- Our analysis does not include the multiple affiliations of many of the authors and so may under-report the level of collaboration. Many other collaborative efforts are not reflected in co-authorship metrics, such as collaborations that continue to occur through co-authorship, grant submissions, and conference presentations.

INTRODUCTION

Over the past two decades, continuous quality improvement (CQI) programs have been widely taken up by primary healthcare (PHC) services caring for Aboriginal and Torres Strait Islander people (hereafter respectfully referred to as Indigenous people, acknowledging their cultural and historical diversity) across Australia.(1, 2) CQI – a set of methods for improving the quality of care, through continuous measurement and problem-solving techniques(3, 4) – has been found to improve the quality of care delivered in Indigenous PHC.(1, 5)

While evidence indicates no single model of CQI outperforms others, the most successful applications of CQI are multi-site and multi-faceted approaches that aim to achieve change at various levels of the health system.(6) We and others have argued the need for multidisciplinary research networks to support the practice and effectiveness of CQI (6, 7) and to foster co-production and sharing of knowledge. However, despite research networks often being touted as a solution for enhancing knowledge translation into policy and practice, their characteristics and emergence over time are poorly understood.(8-10) Furthermore, evaluation challenges can be considerable because research networks are often loosely defined and manifest in different forms with formal and informal organisational structures.(11, 12)

We sought to better understand the development and growth of a multidisciplinary research network in Indigenous PHC quality improvement, and how these aspects reflected the vision of the network with respect to capacity strengthening, equity and membership diversity. Co-authorship network analysis offers one feasible strategy for evaluating the growth and emergence of research networks, because publications are well documented and reflect collaboration.(13-15) The study uses co-authorship network analysis to examine the growth and change in an 18-year CQI research network in Australian Indigenous primary health care. We address the question: How did the research network expand and change over time? Specifically we will investigate the extent to which the research network brought together people from a variety of organisations; the structural characteristics of the network; the level of equity in authorship relative to Indigenous status and gender; capacity strengthening efforts through examining student authorship; and changes in research themes over time.

The setting

Although Australia has a high-performing health system, underpinned by a universal health insurance scheme, it ranks low on measures of equity when compared with other Organisation for Economic Co-operation and Development (OECD) nations.(16) This ranking is reflected in consistent underperformance in addressing inequities in health care access, quality of care and outcomes for Indigenous people.(17-19) These inequities are underpinned by a legacy of colonisation, land

dispossession, displacement, disempowerment, social and economic exclusion, and ongoing racial discrimination.(19, 20)

To help address these inequities, the Audit and Best Practice in Chronic Disease (ABCD) participatory action research program was initiated in 2002. Drawing on international evidence about the effectiveness of system-wide CQI approaches to improve the quality of PHC service delivery,(21) the ABCD program employed a systems approach to support the CQI efforts of PHC services established to provide care for Indigenous Australians.(1, 6, 22) Connected to this research program, in 2010 a national, not-for-profit, CQI support entity – One21seventy – was established to support Indigenous PHC services in implementing CQI cycles using standardised, evidence-based, best practice clinical audit and systems assessment tools. Notably, 175 of the over 275 PHC centres involved provided the research network with de-identified data derived from their use of the CQI tools and processes. The studies published by network members reporting analyses of these data form a comprehensive picture of the quality of PHC received by Indigenous people around Australia. (1) Between 2010 and 2016, ABCD research accounted for 42 of the 60 (70%) peer-reviewed publications identified in a systematic review on CQI in Indigenous PHC in Australia,(2) and also made a significant contribution to international CQI research.(23) Importantly, although there were demonstrated improvements in quality of care in some areas of clinical care, there was continuing wide variation between PHC centres and jurisdictions.(1,5)

Table 1 sets out the four distinct phases of the ABCD program's evolution from 2002 to December 2019, its research aims, systems-strengthening dimensions and main findings. The intention of the resulting network was an 'open collaboration' that actively encourages cooperation with other organisations and individuals to help achieve the program's aims. The current phase of research (2020-24) is included in Table 1 but was not part of this study.

Table 1: Phases and research focus of the ABCD program, an action research project implementing quality improvement in Indigenous PHC, 2002–2019

	Phase 1 Exploring feasibility and acceptability of CQI tools and processes	**Phase 2** Exploring scalability and expansion of CQI	**Phase 3** Supporting wide-scale implementation of CQI and development of Partnership Learning Model		**Phase 4** Embedding CQI approaches in systems	Current Phase (not part of study) Strengthening leadership and engagement in system wide CQI
	ABCD (2002–2004)	**ABCD Extension (2005–2009)**	**ABCD National Research Partnership (2010–2014)**	**One21seventy (2010–2016) service support arm**	**Centre for Research Excellence in Integrated Quality Improvement (CRE-IQI) (2015–2019)**	Centre for Research Excellence in Strengthening Systems for Indigenous Health Care Equity (CRE-STRIDE) 2020–2024[#]
Research aims	Explore whether a CQI approach was feasible and effective in Indigenous PHC.(24)	Identify support requirements for large-scale implementation of the ABCD model.(25)	Understand variation in quality of care and strategies for improvement.(22)	Primarily a service support function. Voluntary contribution of data by services for research purposes, and potential for other involvement of services in research.	— Accelerate and strengthen large-scale CQI efforts. — Explore the feasibility/functioning of an 'innovation platform.'(26, 27)	— Strengthen Aboriginal and Torres Strait Islander research leadership for CQI. — Extend CQI methods to sectors beyond the PHC clinical environment.(28) — Enhance community participation in CQI processes.

Health system strengthening dimension	— Using participatory action research, a CQI process was introduced to 12 Indigenous PHC centres in one jurisdiction (Northern Territory) with a focus on the prevention and management of chronic disease.(29) — CQI approach embraced to improve (and demonstrate) quality of care. — Systems assessment tool provided a mechanism for ongoing local system improvement and integration with other organisations and sectors.(30)	— Geographic scope of the project was extended to include 69 Indigenous PHC services in several jurisdictions across Australia. — Scope was broadened to address other priority areas of PHC, with audit tools for additional areas of care. — Informed health system planning and policy by showing how the ABCD approach could be scaled up, and examined barriers/enablers to engagement and improvement.	— More than 175 Indigenous PHC services across Australia involved in ABCD program.(31) — Brought together stakeholders from across jurisdictions and levels of the health system to support and guide research on priority PHC health system issues, and to contribute to refining CQI tools and processes, interpreting data, applying findings and sharing lessons.(31)	Provided CQI training and tools with systems thinking focus, and web-based data analysis and reporting system able to provide local and aggregated data reports, with benchmarking. 275 + health services used ABCD tools and processes, and more than 2500 PHC staff were trained in the use of CQI tools and processes.(31)	— Adapted and extended the Partnership Learning Model, developed through previous phases of the research, by engaging with a wider range of stakeholders responsible for Indigenous PHC to solve problems and innovate together. — Emphasis on research capacity strengthening and research translation.(32)	— Develop new knowledge to strengthen integration in comprehensive PHC and embed CQI at all levels of the PHC system. — Strengthen Indigenous community input into improving CQI processes. — Extend CQI processes and collaborations across sectors.

Research findings	CQI approach was well accepted, demonstrated the feasibility and application of tools and processes, and showed improvements in care and intermediate health outcomes.	— Identified key barriers and enablers to scaling up in an Indigenous context.(33) — Established the need for further tools to support the implementation of CQI in Indigenous PHC.	— Demonstrated improvements in quality of care in some areas, and continuing wide variation between PHC centres and jurisdictions.(1,5) — Developed Partnership Learning Model to achieve large-scale improvements in quality of care and population health outcomes.(6)	— + 70% of PHC centres engaged in One21seventy provided their de-identified data to the ABCD National Research Partnership for use in research.	— Established that clinical and other areas such as community health promotion and prevention outcomes can be improved by using evidence-based CQI tools and processes.(34) — Identified factors that support the effective use of CQI by PHC teams and services, and improvements in delivery of care.(35) — Identified priorities for strengthening PHC systems to achieve large-scale health improvements.(36, 37)	Not applicable

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NB: ABCD – audit and best practice for chronic disease; CQI – continuous quality improvement; PHC – primary health care; NHMRC – National Health and Medical Research Council

Source: Adapted from Bailie et al. 2013

+ Although the projects were supported by research funding, it is important to note there were financial contributions and in-kind support from a range of community-controlled and government agencies.

CRE-STRIDE is the current form of the network, and its successful funding underscores the research program's longevity and stability.

METHODS

We used social network analysis, as described by Fonseca and co-authors(13) in their health sector co-authorship network analysis, to retrieve scientific publications, standardise entries for authors and organisations, visualise the network and calculate metrics.

Data retrieval

Details of peer-reviewed journal articles and books (the 'publications') were retrieved from administrative records held by the Centre for Research Excellence in Integrated Quality Improvement (CRE-IQI) coordinating centre, and included all publications published from 2002–2019.

Data categorisation, standardisation, and cleaning

Publications were sorted into categories and research themes that were iteratively developed and defined by JB and RSB. We describe the process for categorisation of included publications below.

Organisations: the affiliations of the authors (as per their citation on publications) were coded into Universities and Research Institutes; Government Departments; Health Services; Affiliates; Primary Health Networks; and Non-Government Organisations. Where authors had more than one affiliation listed on the publication, we used the first affiliation provided. Other key points in the categorisation of publications were as follows:

- We used the author's University rather than their specific Department and, if named, the Research Institute rather than the University.
- Where an author's affiliation was nominated as a hospital we used the State Health Department with which these organisations were affiliated.
- 'Affiliates' refers to regional support organisations established to support Indigenous health services, such as Aboriginal Medical Services Alliance Northern Territory.
- 'Health Service' refers to services established primarily to provide PHC to Indigenous people, and includes Aboriginal community-controlled services, Government services, and private General Practice.
- Primary Health Networks refer to independent regional PHC organisations across Australia that commission rather than provide services, as established by the Australian Government in July 2015.
- Non-Government Organisations refer to not-for-profit organisations that operate independently of Government, typically with the purpose of addressing a social or political issue.

Research themes*:* Publications were assigned to one of the following three research themes:

1. *CQI-related program activities that address clinical care delivery in the PHC setting:* publications that focus on the quality, and variations in delivery, of clinical care, and the application of, or learning from, CQI techniques in relation to a specific aspect of clinical care, e.g., child health and chronic illness care.
2. *CQI-related program activities that address social, environmental or behavioural determinants – i.e. community health promotion or prevention activities:* publications that focus on the application of, or learning from, CQI with a focus on areas such as health promotion, social and environmental conditions, housing, food security, and family wellbeing in general community settings.
3. *CQI-related processes and approaches:* publications related to CQI program development (such as study protocols and reviews informing CQI approaches), health systems strengthening, and the development and evaluation of research collaborations and their impact.

In categorising the publications by research themes, abstracts of publications were retrieved and screened by blinded reviewers (JB and RSB). Inconsistencies in reviewer assessments were resolved by consensus.

Role type: We identified all authors who were students or project officers at the time of the publication, and who had authored in this capacity. The student category included Public Health Trainees, and Masters, PhD, and Medical Honours students. Project officers were identified as those whose primary role supported research, and/or related either to health care administration and/or to project work.

Indigenous status*:* Coordinating centre records flagged authors who identified as Indigenous.

Gender: Authors were assigned a male or female category through a number of ways – reviewer knowledge of authors and Google searches.

Where there was uncertainty in allocating the above categories, JB checked with RSB and, when necessary, with the corresponding authors of the manuscripts. Data were entered into an Excel spreadsheet, and then standardised and cleaned by JB and BAP.

Network assembly, visualisation and analysis

The evolution of the research network was analysed over the four phases displayed in Table 1, with the analysis split into three parts: 1) an analysis of publications by type of organisation represented, research themes, the role of authors, and the Indigenous status of authors; 2) the network analysis of co-authorship between organisations; and 3) a core-periphery analysis of organisational position within the network.

Python programming language version 3.7.4(38) and the *Jupyter Notebook*(39) application accessed through the *Anaconda Navigator*(40) interface were used to script all data manipulation and analytical

work. Network analyses used the Python package *NetworkX*,(41) with visualisations produced with the open-source *Gephi* program.(42)

We first created a node list containing every organisation and its attributes (unique identifier, organisation name, type and years published), and an edge list representing co-authorship as pairwise combinations of each organisation listed on a publication and its unique attributes.

A single, undirected edge of weight=1 was assigned for each organisation pair that shared at least one publication in each phase of the network. For publications that involved only authors from the same organisation, a self-loop edge of weight=0 was assigned. No additional weight was given to the number of publications or authors involved or any other attribute. This approach was chosen so that results of the analysis could be directly interpreted in the context of inter-organisational collaboration.

Networks were analysed discretely across the four phases. Several network measures (defined in Table 2) were used to understand the resulting networks.

Table 2: Theoretical definitions of social network analysis measures, and their meaning in this study

Measure	**Definition, meaning in this study, and importance**
Node	The basic unit of a network. Nodes represent organisations. The node size is proportional to the number of publications.
Edge or Tie	An edge or tie connects two nodes in a network, and indicates a relationship between the two. An edge between two organisations indicates co-authorship of at least one publication.
Density	The density of a network is the total number of edges divided by the total number of possible edges. It is a widely used measure that reflects the level of cohesion among network organisations, or the extent to which organisations collaborated with every other organisation in the network.
Average degree	Degree is a count of the number of connections for any given node: the higher the average degree, the more connected the network. The average number of inter-organisational collaborations per organisation.
Clustering co-efficient	Clustering is a measure of how many of the nodes connected to a given node are also connected to each other, which is expressed as a proportion of the total possible connections. The overall clustering co-efficient is the average across the network. Where density tells you how connected the network is, the clustering co-efficient tells you how well connected the various neighbourhoods of the network are. A high clustering co-efficient and low density can be an indication of lots of small groups, loosely connected.

Path/path length	The path is any connected series of edges between two nodes. The length of a path is the number of steps (edges) and shows how quickly organisations can communicate with each other through their links.
Geodesic distance	The geodesic distance is the shortest path of all possible options between two nodes in the network. The number of steps it takes to get across a network is a useful measure of how quickly information can be disseminated to the entire network.
Diameter	The diameter of the network is the 'longest short path' between nodes and indicates the maximum number of steps it would take to get between nodes that are furthest away from each other in the network. The diameter gives a useful indication of how broad the network is.
Centralisation	This reflects how tightly the organisations are connected around the most central point of the network and how reliant the network may be on a central node.
Discrete core-periphery model	A network with a core-periphery structure has a 'core' of nodes densely connected to each other and to others, and 'periphery' nodes in the less-connected 'periphery' that are connected only to core nodes.

The analysis of network position at the organisational level uses discrete core-periphery analysis(43) to identify organisations that are well connected to each other (the core) as distinct from those less well connected (the periphery). To detect the core-periphery, we used the Borgatti and Everett(43) algorithm and the non-parametric statistical test devised by Kojaku and Masuda(44).

Patient and public involvement

No patients or members of the public were involved in the design, analysis or reporting of this study.

RESULTS

We identified 128 publications written by 308 authors, with a median of six authors per publication (Interquartile Range = 4–9.25), representing 79 different organisations (Table 3). Most authors (182 or 59.5%) contributed just one publication, while 18 (5.9%) contributed 10 or more. The chief investigator (RSB) of the original ABCD program co-authored 97 of the 128 publications (Supplementary File 1).

Table 3: Co-authorship characteristics, by phases and total 2002–2019

Indicator	Phase 1: 2002–2004	Phase 2: 2005–2009	Phase 3: 2010–2014	Phase 4: 2015–2019	Total: 2002–2019

Number of publications		2	15	21	90	128
Number of different authors		5	33	67	263	308
Number of authors per paper (median, IQR)		5, [5 - 5]	5, [3.5 - 8.5]	9, [4 - 13]	6, [5 - 9]	6, [4 - 9.25]
Organisational involvement						
Number of nodes (organisations)		3	12	24	72	79
Number and type of different organisations	University or Research Institute	3	8	15	45	48
	Government Department	–	2	3	9	10
	Affiliate	–	1	4	2	5
	Health Service	–	1	2	11	11
	Non-Government Organisation	–	–	–	4	4
	Primary Health Network	–	–	–	1	1
Number of publications with an author who has an international affiliation		0	1	0	8	9
Capacity strengthening						
Number and percentage of publications with a student/project officer as a lead author		0 (0%)	2 (13%)	3 (14%)	25 (28%)	30 (23%)
Number and percentage of publications with at least one student/project officer as an author		2 (100%)	12 (80%)	13 (62%)	52 (58%)	79 (62%)
Addressing equity						
Number and percentage of female authors		1 (25%)	20 (60%)	39 (58%)	171 (65%)	192 (62%)
Number and percentage of publications with a female first author		0 (0%)	2 (13%)	14 (67%)	76 (84%)	92 (72%)
Number and percentage of publications with a female last author		0 (0%)	4 (27%)	6 (29%)	25 (28%)	35 (27%)
Number and percentage of publications with at least one Indigenous author		0 (0%)	6 (40%)	13 (62%)	56 (62%)	75 (59%)
Number and percentage of publications with an Indigenous lead author		0 (0%)	0 (0%)	2 (10%)	3 (3%)	5 (4%)
Number and percentage of publications with an Indigenous last author		0 (0%)	3 (20%)	0 (0%)	0 (0%)	0 (0%)
Thematic trends in publications						

Thematic areas, number and percentage	CQI-related activities in clinical care	2 (100%)	6 (40%)	8 (38%)	44 (49%)	60 (47%)
	CQI activities in areas such as community-based health promotion and prevention	0	2 (13%)	5 (24%)	16 (18%)	23 (18%)
	Processes and approaches for CQI	0	7 (47%)	8 (38%)	30 (33%)	45 (35%)
Co-authorship network structural characteristics						
Density		1	0.45	0.47	0.11	0.13
Average degree (organisations)		2	5	10.9	8.1	9.8
Centralisation (degree)		0	0.65	0.57	0.55	0.53
Clustering		1	0.80	0.86	0.81	0.79
Geodesic distance		1	1.5	1.5	2.1	2.1
Diameter		1	2	2	3	3
Core-periphery structure		0	1 (p=.03)	1 (p=.01)	1 (p<.001)	0.42 (p=.83)

CQI: continuous quality improvement; IQR: interquartile range

Linking people from a variety of organisations

As shown in Table 3, there was an increase in the number and type of different organisations in the network, with considerable growth from Phase 3 (24 organisations) to Phase 4 (72 organisations). Of note, the number of Universities and Research Institutes increased from 15 in Phase 3 to 45 in Phase 4, while Health Services rose from 2 to 11 and international organisations increased to 8. This growth in different organisations participating in the research network over time was a result of existing organisations continuing to publish together (yellow nodes), and new organisations co-authoring (blue nodes) (Figure 1). A few organisations ceased publishing as part of the network (red nodes), shown as 'isolates'.

[INSERT FIGURE 1]

Figure 1: Evolution of the quality improvement research network, 2002–2019

Relationships of organisations and structural characteristics

The structural characteristics of the networks are based on the indicators shown in Table 3. Our analysis of the network data shows a decrease in the network density. In Phase 2 and 3, the research network was relatively well connected with ~46% of all possible relationships in the network actualised. However, in Phase 4, with ~11% of all possible links existing between organisations, there was less connectivity between organisations. The decrease in network density was linked to an increase in the

number of organisations publishing together in Phase 4, as noted above (Table 3), and an increase in the scope of CQI publications. However, the average clustering coefficient remained high across all phases (1, 0.80, 0.86, and 0.81 respectively), indicating a strong tendency for multiple organisations to be collaborating on individual publications. Part of this high effect is a natural consequence of authors publishing together – it introduces triangles of collaborating authors, thereby increasing the clustering co-efficient.

From Table 3, we note that the average number of organisations collaborating directly on publications (average node degree) steadily increased from 2 in Phase 1, to 5, 10.9, and then 8.1 in subsequent phases. This is a sign that organisations collaborated more widely over time, with a small decrease in Phase 4. On average, publications involved 3.4 organisations, with 3.5 publications per organisation. This indicates a maturation of organisational relationships, typically creating more than one publication from each collaboration. Furthermore, network diameter was at-most 3 (Phase 4) and geodesic distance was at-most 2.1 (Phase 4). This indicates a close-knit cohesive network in which organisations were connected by no more than two other organisations, resulting in the network being unlikely to fragment and able to disseminate information quickly.

The degree-centralisation from Phase 2 was 0.65 followed by 0.57 and 0.55 in the subsequent phases. Conversely, the core-periphery analysis produced strong results in each phase (see Table 3). These analyses indicate that in all four phases the network was not connected via a single dominant central organisation but rather by a core-periphery structure that points to a more collaborative network. Intersectoral collaboration (research, government and/or health services) were represented in the core for phases 2 and 3 (green nodes in Figure 2). In Phase 4, the organisations comprising the core were all Universities or Research Institutes, indicating that Government Departments and Health Services were more likely to publish with them than with each other.

[INSERT FIGURE 2]

Figure 2: Core periphery analysis by phases, 2002–2019

Equity in authorship

Female first authors increased over time, growing from none in Phase 1 to 84% (n=76) in Phase 4 (Table 3), with about 28% of the publications having a female senior or last author in all phases after the first. Although the number of publications led by Indigenous authors remained low, over time there was an increasing number and percentage with at least one Indigenous author. The greatest expansion was observed from Phase 3 to Phase 4 when the number of publications with at least one Indigenous author increased from 13 to 56 (Table 3).

Providing opportunities for capacity strengthening

Over time there was also an increase in absolute number (but a decline in percentage) of publications with at least one student or project officer author, from 2 in Phase 1 to 52 in Phase 4 (Table 3). Phase 4 also saw an increase in student or project officer as lead author, with the largest growth in Phase 4 (28%, n=25) representing a two-fold increase from Phase 3 (14%, n=3).

Expansion of research themes

As the network evolved there was a notable growth in publications related to CQI and clinical care, an increase in publications related to social, environmental and behavioural determinants of health, and on the development of processes and approaches for CQI (Table 3). The growth in research themes in Phase 4 was consistent with the increase observed in the number of publications and organisations involved in this phase, and the emergence of new core organisations. Supplementary File 2 contains a listing of all publications and their assigned category of research themes.

DISCUSSION

This study examined the growth of and changes in an Australian quality improvement research network over an 18-year period by assessing co-authorship of publications using network analysis. Key findings include an expansion in the number of publications; a greater number and diversity of organisations co-authoring; improvements in capacity strengthening measures reflected in increased student and project officer authorship and first author position; and a broadening or scaling-out(45) of quality improvement work to other thematic areas. There is evidence, too, that the research network linked people from a variety of organisations, including Universities or Research Institutes, PHC services and Government Departments, who might otherwise have never worked together. This expansion potentially extended both the impact of the network and of the organisations involved.

The characteristics of the network showed a strong collaborative structure and a maturation of organisational relationships, with more than one publication typically developed by each collaborating organisation. Network analyses indicated a core-periphery structure of organisations connected to each other in each phase, rather than a network structured around a single central organisation. As there was the same Chief Investigator throughout the study period, this finding of a core-periphery structure indicates the network expanded to have other core organisations over time, and was not just centred on the Chief Investigators organisation. In phases 2 and 3, the relationships between research institutions and government departments were well represented in the network core. The network's founding partners maintained a consistent presence as members of the core, indicating that it remained dependent on these partners for collaboration. However, new core organisations emerged when key authors changed institutions, reflecting that individuals stimulated the expansion of core members. For example, a result of key individuals moving institutions and growing the publishing base was a Phase 4 core comprised solely of Universities and Research Institutes, while Health Service and Government

Organisations were part of the core in the earlier phases. This change occurred despite a large increase in the number and type of organisations involved in the network in Phase 4.

Network growth was greatest in Phase 4, when funding was received from the Australian Government's NHMRC to establish a Centre for Research Excellence and the network's structure and function(12) evolved to that of an 'innovation platform.'(26) Used as a vehicle to stimulate and support multi-stakeholder collaboration and learning, 'innovation platforms' provide a space of interaction to facilitate the development and emergence of innovations when there are complex, system-wide issues requiring coordinated action and collective problem solving. Most extensively applied in international agricultural development, and to a limited extent in health, innovation platforms differ from other networks by the incorporation of a wider network of stakeholders at multiple levels of the system and in different roles; the concept of "sector boundary spanning" that brings in stakeholders from other sectors to assist in developing health care solutions; and application of continuous reflection, learning and adaptation as central design elements.(26, 27)

These findings support previous literature that researchers tend to collaborate with like-minded others, but that this tendency toward homophily can be disrupted by implementing policies that encourage interdisciplinary collaboration and purposeful research translation – such as was done with the innovation platform.(14) Although the purposeful adjustment to an 'innovation platform' was associated with an expansion of activity among the network and new thematic scope in publications, this acceleration could also reflect other inter-related factors, such as longer-term relationships, and an increase in funding.

Furthermore, the earlier phases were focused on supporting PHC services to implement and embed quality improvement techniques through participatory action research. Access to the CQI dataset formed the basis of research collaborations between those services and University and Research Institutes to undertake data analyses that resulted in publications up to 2019. Though there were 175 PHC services providing data to the research collaboration, only 11 Health Services co-authored publications. While not necessarily co-authors, Health Services made important contributions to implementing research, collecting data, and importantly – to interpretation and analysis of findings.

Our findings build on a prior social network analysis of partners in the research network which was undertaken as part of an interim evaluation in Phase 3 of the research network. Cunningham and her co-authors(46) found an increase in network density (43% to 59%) from 2013 to 2014, indicating an increase over time in connectivity and communication between partner organisations. A major element in achieving the goals of that phase of research was the network's focus on developing a shared database of de-identified CQI data from Indigenous PHC centres.(46) The importance to the research network of collecting and sharing data is supported by the experiences of other research collaborations.(47, 48) Furthermore, the high level of trust identified across the network is indicative of a properly functioning

collaboration.(49) The growth in Phase 4 leveraged the high level of trust already established. The decreasing degree of centralisation scores are consistent with findings reported by Cunningham et al.(46), and reflect the shift towards more organisations taking a greater role in publishing. Increasing the number of diverse collaborations and creating a more decentralised network has been shown to improve productivity and increase the potential for high-impact science.(50)

Equity and capacity strengthening are promoted as core elements of research networks.(12, 51) The research network, particularly when operating as an innovation platform, made some progress in addressing concerns about the imbalances between Indigenous and non-Indigenous authors when writing about Indigenous issues. However, despite an increased number of publications with Indigenous authors, especially in Phase 4, there remains a paucity of Indigenous first or senior/last authors. Further work is needed to redress the inequities these imbalances represent, a concern echoed in global health literature.(52) The latest iteration of the research network was recently launched with funding for a new Centre for Research Excellence in Strengthening Systems for Indigenous Health Care Equity (2020–2024) (CRE-STRIDE) (NHMRC Grant Id #1170882). This Centre marks the beginning of a new Indigenous leadership structure for the research network with more than half of the research investigators, including the Chief Investigator, identifying as Indigenous. It also aims to extend and further support the use of CQI methods in sectors with responsibility for addressing social and cultural determinants of health and to enhance community participation in CQI processes.(28)

Strengths and limitations of the study

A study strength was the long timeframe of 18 years of publications. Although co-authorship is only one indicator of collaboration, there are several advantages to relying on it as a proxy for assessing the level of research collaboration, including its verifiability, stability over time, availability of data in the public domain and ease of measurement.(11)

As the aim of the study was to assess growth and change in the research collaboration over time, we applied an unweighted method to the network analysis. This approach was chosen for a number of reasons. Firstly, the interpretability would be compromised by weighting edges, in the context of the questions we wished to answer. We moved all of the information that would have otherwise been embedded into a weight to separate descriptive analyses available in Table 3. Secondly, given the temporal nature of collaborations we did not wish to make erroneous assumptions that quantity of publications is a substitute for quality. For example, it is difficult to compare a collaboration that generates only one high impact publication to a collaboration that may produce a larger number of lower impact publications. Weighting by publication numbers could therefore introduce a bias that may lead to erroneous interpretation of the findings.

Limitations of this study include: 1) many collaborative efforts are not reflected in co-authorship metrics. We are undertaking other studies to address this as part of the overall evaluation of the CRE-IQI. Other measures of collaborative ties include having co-investigators on submitted or funded grants, on conference presentations and as authors of grey literature, all of which may be useful to broaden the definition of collaboration in our innovation platform. However, we assumed that, in most cases, co-authorship indicates an active cooperation between partners beyond the simple exchange of material or information. 2) This analysis does not capture the collaborations that continue to occur through co-authorship or other means that are not necessarily related to the research network. For example, a collaboration formed by co-authoring on a CRE-IQI manuscript might lead to collaboration on other projects and research not reflected in this analysis. 3) Because there is a substantial lead-time for an academic publication, a writing collaboration that might have commenced in an earlier phase of work may not have been published until a later phase. Thus publication in one phase can arise from substantial work in a previous phase. 4) Although multiple authorship affiliations are increasingly recognised as facilitating knowledge exchange and becoming more widespread,(53) our analysis does not include the multiple affiliations of many of the authors and so may under-report the level of collaboration. Similarly, only representing the University affiliation, and not the actual Department in which an author works, obscures collaboration between Departments in the same University. 5) Three of the eleven authors on this manuscript (RSB, JB and VM) had published more than 20 manuscripts included in this analysis, and RSB was the Chief Investigator on the research network during this period. Given this, and to mitigate against bias, BP who has not published as part of this network undertook the network analysis and a blind review process for categorising the manuscripts, with discrepancies discussed.

To the best of our knowledge, this study is the first to describe a CQI research network using co-authorship network analysis. While the generalisability of the findings may be limited to similar networks, the methodological approach could readily be transferred. In this study we did not set out to demonstrate a link between an expansion of the collaboration and engagement with impact or improvement in the quality of care. However, it is widely recognised in the literature, that increasing collaboration and engagement across health services, researchers and policy makers is a critically important element along the causal change pathway to improving the quality of care and achieving impact. Methods such as co-authorship analysis are useful for demonstrating a pathway to research impact related to engagement, which traditionally tends to rely on the quantity of outputs rather than on the strengthening of networks and the scope of work undertaken.

CONCLUSION

Over the 18-year timeframe, collaboration in publications increased with network consolidation and expansion. Publication outputs accelerated in the final phase, coinciding with a broader thematic focus

and an increase in the number and diversity of participating organisations. This expansion occurred largely due to the cumulative effect of building trust and relationships over time, including the development of a comprehensive dataset for use by all stakeholders. The findings highlight the benefits of long-term relationship building among diverse partners to support participatory research in quality improvement. Increased productivity was associated with increased authorship diversity and a decentralised network, suggesting these may be important factors in enhancing research impact and advancing the knowledge and practice of CQI in primary health care. Despite improvements, further work is needed to address inequities in female authorship and Indigenous authorship. The co-authorship analysis has been useful for demonstrating research impacts related to collaboration, which are not well captured by metrics such as quantity of outputs.

Declarations

Ethics approval: University of Sydney Human Research Ethics Committee (Project 2018/206) and the Human Research Ethics Committee of the Northern Territory Department of Health and Menzies School of Health Research (Project 2018-3105).

Consent for publication: Not applicable

Availability of data and material: Not applicable

Competing interests: The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Author's information: RSB was the Chief Investigator of the research network from 2002 – 2019. RSB, JB, VM, AL, FCC, RGB, and AL had published 5 or more publications as part of this research network. RGB and VM are both Indigenous researchers: RGB is from the Gungarri/Kunja nations in South-Western Queensland and VM from the Quandamooka community on North Stradbroke Island, Queensland. JB, BAP, RSB, DP, AL, SA, KPC, MEP and FCC are non-Indigenous researchers. All authors have a long-standing commitment to improving health outcomes for Aboriginal and Torres Strait Islander people.

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Authors' contributions: JB, BAP and RSB conceived the manuscript, with JB taking the lead on writing on all drafts, integrating feedback upon reviews and finalising the manuscript. BAP undertook the analysis and provided input into the drafting of the methods and conceptual design. All authors contributed to revisions of the manuscript and approved its final version.

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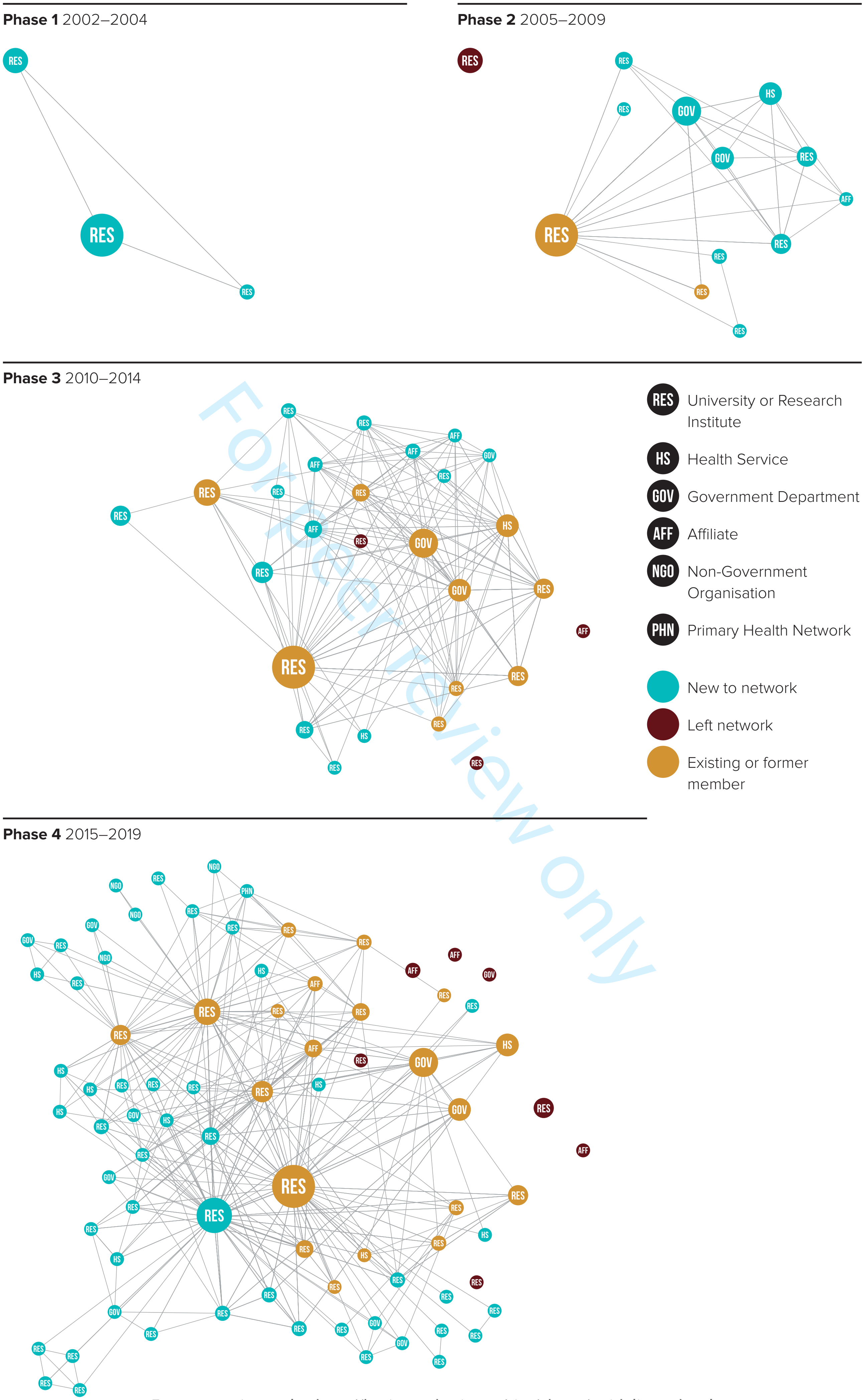
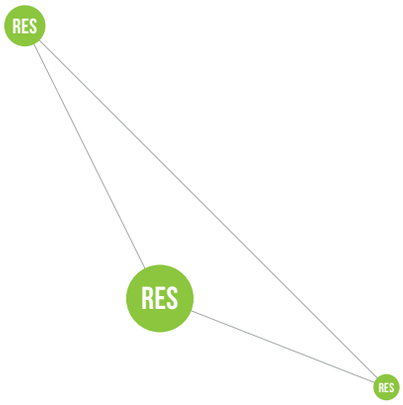


Phase 1 2002–2004



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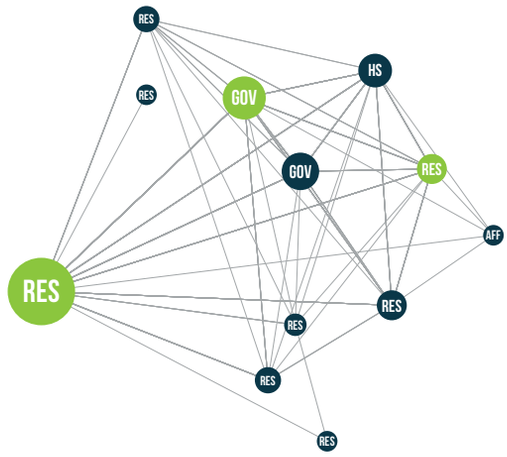
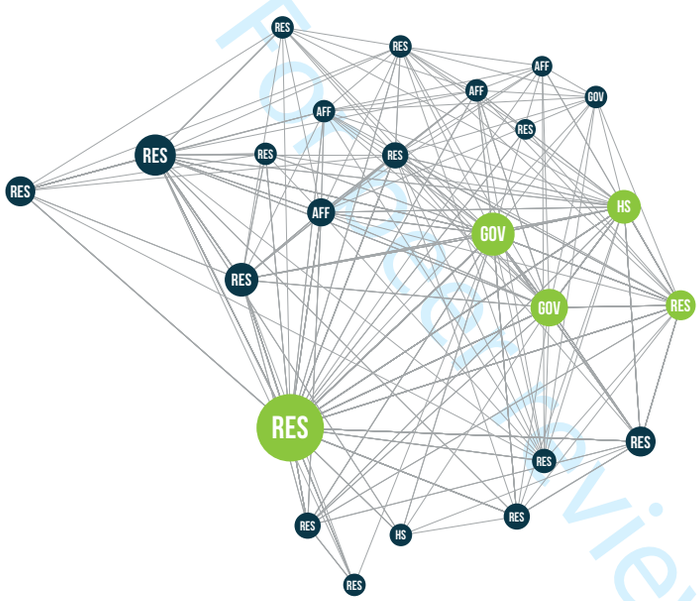
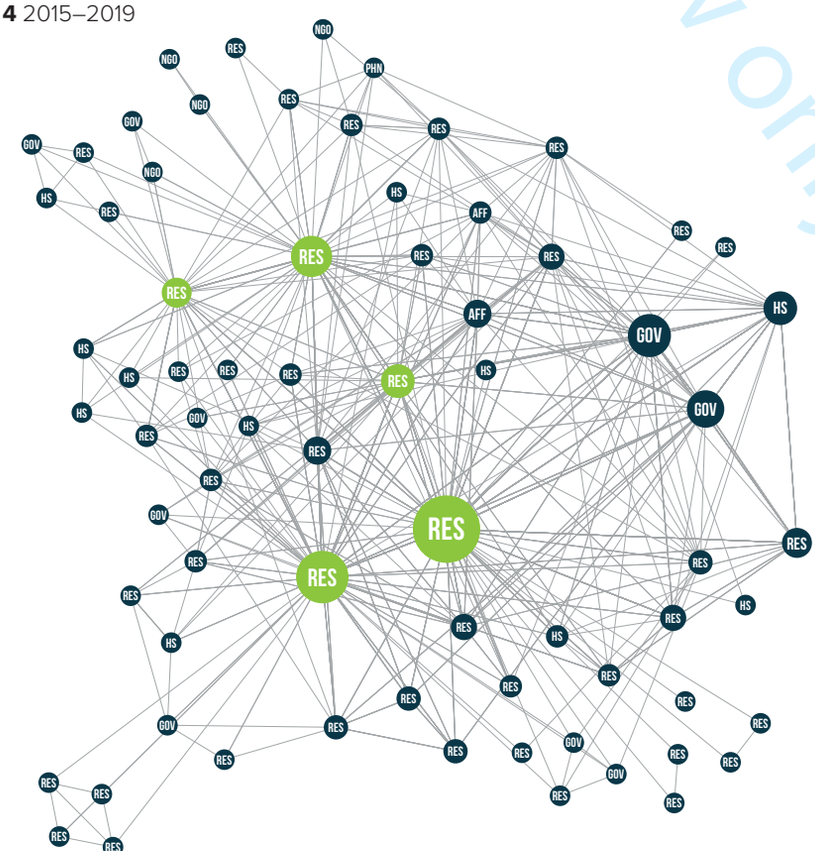


Phase 3 2010–2014



Phase 4 2015–2019



SUPPLEMENTARY FILE 1

Table S1: Total number of publications, per author, for those who have published 5 or more as part of the research collaboration, 2002–2019

Author name (last_first)	Total number of publications
Bailie_Ross	97
Matthews_Veronica	36
Thompson_Sandra	21
Tsey_Komla	21
Bailie_Jodie	21
Si_Damin	20
Connors_Christine	20
Dowden_Michelle	17
O'Donoghue_Lynette	15
Weeramanthri_Tarun	14
Larkins_Sarah	13
Kennedy_Catherine	12
Schierhout_Gill	12
Cunningham_Frances	12
Clelland (Percival)_Nikki	11
Laycock_Alison	11
Kwedza_Ru	10
Bainbridge_Roxanne	10
Cox_Rhonda	9
Brown_Alex	9
McCalman_Janya	9
Robinson_Gary	8
Liddle_Helen	8
Burke_Hugh	8
Rumbold_Alice	7
Boyle_Jacqueline	7
Gardner_Karen	6
Ralph_Anna	6
Burgess_Paul	6
Nagel_Tricia	5
Moore_Elizabeth	5

Doran_Chris	5
Garvey_Gail	5
Valery_Patricia	5
Kinchin_Irina	5
McAullay_Dan	5
McAuley_Kimberley	5
Strobel_Natalie	5
Edmond_Karen	5
Onnis_Leigh-Ann	5

SUPPLEMENTARY FILE 2

Table S1: Publications included in the analysis, phase and research theme allocation, 2002–2019

	Phases of research collaboration				Categories of research themes		
	Phase 1: 2002 – 2004	Phase 2: 2005 – 2009	Phase 3: 2010 – 2014	Phase 4: 2015 – 2019	CQI in PHC Clinical care	CQI activities in social, environmental or behavioural determinants	Processes and approached for CQI
Bailie RS, Togni SJ, Si D, et al. Preventive medical care in remote Aboriginal communities in the Northern Territory: a follow-up study of the impact of clinical guidelines, computerised recall and reminder systems, and audit and feedback. *BMC Health Serv Res* 2003;3(1):15.	1				1		
Bailie RS, Si D, Togni SJ, et al. A multifaceted health-service intervention in remote Aboriginal communities: 3-year follow-up of the impact on diabetes care. *MJA* 2004;181(4):195–200.	1				1		
Si D, Bailie R, Connors C, et al. Assessing health centre systems for guiding improvement in diabetes care. *BMC Health Serv Res* 2005;5(1):56.		1			1		
Wayte KJ, Bailie RS, Stephenson P. Improving the feedback of housing information to Indigenous communities. *Environmental Health* 2005;5(2):36.		1				1	
Bailie RS, Wayte KJ. A continuous quality improvement approach to Indigenous housing and health. *Environmental Health* 2006;6(2):36–41.		1				1	
Bailie RS, Robinson G, Kondalsamy-Chennakesavan SN, et al. Investigating the sustainability of outcomes in a chronic disease treatment programme. *Soc Sci Med* 2006;63(6):1661–70.		1			1		
Bailie R, Si D, Dowden M, et al. Improving organisational systems for diabetes care in Australian Indigenous communities. *BMC Health Serv Res* 2007;7(1):67.		1			1		
Bailie RS, Si D, O'Donoghue L, et al. Indigenous health: effective and sustainable health services through continuous quality improvement. *MJA* 2007;186(10):525–7.		1					1
Si D, Bailie RS, Dowden M, et al. Delivery of preventive health services to Indigenous adults: response to a systems-oriented primary care quality improvement intervention. *MJA* 2007;187(8):453–7.		1			1		

McDonald EL, Bailie RS, Rumbold AR, et al. Preventing growth faltering among Australian Indigenous children: implications for policy and practice. *MJA* 2008;188:S84–S6.		1					1
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The RECORD statement – checklist of items, extended from the STROBE statement, that should be reported in observational studies using routinely collected health data.

	Item No.	STROBE items	Location in manuscript where items are reported	RECORD items	Location in manuscript where items are reported
Title and abstract					
	1	(a) Indicate the study's design with a commonly used term in the title or the abstract (b) Provide in the abstract an informative and balanced summary of what was done and what was found	Title and abstract	RECORD 1.1: The type of data used should be specified in the title or abstract. When possible, the name of the databases used should be included. RECORD 1.2: If applicable, the geographic region and timeframe within which the study took place should be reported in the title or abstract. RECORD 1.3: If linkage between databases was conducted for the study, this should be clearly stated in the title or abstract.	Title and abstract Abstract, though some information in title also. NA
Introduction					
Background rationale	2	Explain the scientific background and rationale for the investigation being reported	Introduction paragraphs 1 -3		
Objectives	3	State specific objectives, including any prespecified hypotheses	Introduction paragraph 3		
Study Design	4	Present key elements of study design early in the paper	Title, Abstract, Introduction and Methods		
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	Setting described, specifically see Table 1; along with time periods (2002-		

			2004; 2005-2009; 2010-2014; 2015-2019)		
Participants	6	*(a) Cohort study* - Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study* - Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study* - Give the eligibility criteria, and the sources and methods of selection of participants *(b) Cohort study* - For matched studies, give matching criteria and number of exposed and unexposed *Case-control study* - For matched studies, give matching criteria and the number of controls per case	Persons and the organisations they were affiliated with were included if they co-authored a relevant publication in the study period as described in methods.	RECORD 6.1: The methods of study population selection (such as codes or algorithms used to identify subjects) should be listed in detail. If this is not possible, an explanation should be provided. RECORD 6.2: Any validation studies of the codes or algorithms used to select the population should be referenced. If validation was conducted for this study and not published elsewhere, detailed methods and results should be provided. RECORD 6.3: If the study involved linkage of databases, consider use of a flow diagram or other graphical display to demonstrate the data linkage process, including the number of individuals with linked data at each stage.	Persons and the organisations they were affiliated with were included if they co-authored a relevant publication in the study period as described in methods. NA NA
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable.	Definitions of categories provided in manuscript. In Methods section under heading 'Data categorisation, standardisation and cleaning'	RECORD 7.1: A complete list of codes and algorithms used to classify exposures, outcomes, confounders, and effect modifiers should be provided. If these cannot be reported, an explanation should be provided.	Definitions of categories provided in manuscript. In Methods section under heading 'Data categorisation, standardisation and cleaning'

Data sources/ measurement	8	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	Detailed in results - Table 3		Detailed in results – Table 3.
Bias	9	Describe any efforts to address potential sources of bias	Detailed in methods, eg. Having two authors undertaking categorisation in a blind manner, then conferring for any discrepancies; group analysis processes by reviews of co-authors.		Detailed in methods, eg. Having two authors undertaking categorisation in a blind manner, then conferring for any discrepancies; group analysis processes by reviews of co-authors.
Study size	10	Explain how the study size was arrived at	Detailed in methods – eg Publications within the period under study.		Detailed in methods eg. Publications within the period under study.
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen, and why	NA		
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding (b) Describe any methods used to examine subgroups and interactions	NA		

		(c) Explain how missing data were addressed (d) *Cohort study* - If applicable, explain how loss to follow-up was addressed *Case-control study* - If applicable, explain how matching of cases and controls was addressed *Cross-sectional study* - If applicable, describe analytical methods taking account of sampling strategy (e) Describe any sensitivity analyses			
Data access and cleaning methods		..		RECORD 12.1: Authors should describe the extent to which the investigators had access to the database population used to create the study population. RECORD 12.2: Authors should provide information on the data cleaning methods used in the study.	Noted in Methods eg. Internal project records used. Publications retrieved from publicly available sources.
Linkage		..		RECORD 12.3: State whether the study included person-level, institutional-level, or other data linkage across two or more databases. The methods of linkage and methods of linkage quality evaluation should be provided.	NA
Results					
Participants	13	(a) Report the numbers of individuals at each stage of the study (*e.g.*, numbers potentially eligible, examined for eligibility, confirmed eligible, included in		RECORD 13.1: Describe in detail the selection of the persons included in the study (*i.e.,* study population selection) including filtering based on data quality, data availability and linkage. The selection of included persons can	Noted in methods – eg. Persons and the organisations they were affiliated with were included if

		the study, completing follow-up, and analysed) (b) Give reasons for non-participation at each stage. (c) Consider use of a flow diagram		be described in the text and/or by means of the study flow diagram.	they co-authored a relevant publication in the study period as described in methods.
Descriptive data	14	(a) Give characteristics of study participants (*e.g.*, demographic, clinical, social) and information on exposures and potential confounders (b) Indicate the number of participants with missing data for each variable of interest (c) *Cohort study* - summarise follow-up time (*e.g.*, average and total amount)	Table 3 in the results contains characteristics of study participants.		
Outcome data	15	*Cohort study* - Report numbers of outcome events or summary measures over time *Case-control study* - Report numbers in each exposure category, or summary measures of exposure *Cross-sectional study* - Report numbers of outcome events or summary measures	NA		
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (e.g., 95% confidence interval). Make clear which confounders were adjusted for and why they were included (b) Report category boundaries when continuous variables were categorized	In results in Table 3 eg. (b) Phases of the network (time) were based on funding cycles.		

		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period			
Other analyses	17	Report other analyses done—e.g., analyses of subgroups and interactions, and sensitivity analyses	Table 3 in results eg. Descriptive counts and percentages. Network measures as described in methods section.		
Discussion					
Key results	18	Summarise key results with reference to study objectives	Paragraph 1 of Discussion		
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	Discussion – under heading 'strengths and limitations'	RECORD 19.1: Discuss the implications of using data that were not created or collected to answer the specific research question(s). Include discussion of misclassification bias, unmeasured confounding, missing data, and changing eligibility over time, as they pertain to the study being reported.	NA
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	Discussion - The results of the study are compared to findings from other national and international studies.		
Generalisability	21	Discuss the generalisability (external validity) of the study results	Discussion - The lack of generalisability to other settings is noted		
Other Information					
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable,	Funding source provided to the BMJ Quality and Safety		

		for the original study on which the present article is based	Journal, though it is not in the article (at this stage) for the Journal has a triple blind review process.		
Accessibility of protocol, raw data, and programming code		..		RECORD 22.1: Authors should provide information on how to access any supplemental information such as the study protocol, raw data, or programming code.	Noted in the BMJ Quality and Safety submission process that the data is available on reasonable request to the corresponding author, and it adheres to the ethics approval.

*Reference: Benchimol EI, Smeeth L, Guttmann A, Harron K, Moher D, Petersen I, Sørensen HT, von Elm E, Langan SM, the RECORD Working Committee. The REporting of studies Conducted using Observational Routinely-collected health Data (RECORD) Statement. *PLoS Medicine* 2015; in press.

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Collaboration and knowledge generation in an 18- year quality improvement research program in Australian Indigenous primary health care: a co-authorship network analysis

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TITLE PAGE

Title

Collaboration and knowledge generation in an 18- year quality improvement research program in Australian Indigenous primary health care: a co-authorship network analysis

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Key words

Quality improvement; collaboration; research networks; social network analysis; co-authorship network analysis; evaluation; innovation platforms; partnership research

ABSTRACT

Objectives

Though multidisciplinary research networks support the practice and effectiveness of continuous quality improvement (CQI) programs, their characteristics and development are poorly understood. In this study we examine publication outputs from a research network in Australian Indigenous primary health care (PHC) to assess to what extent the research network changed over time.

Setting

Australian CQI research network in Indigenous PHC from 2002 - 2019.

Participants

Authors from peer-reviewed journal articles and books published by the network.

Design

Co-author networks across four phases of the network (2002–04; 2005–09; 2010–14; 2015–19) were constructed based on author affiliations and examined using social network analysis methods. Descriptive characteristics included organisation types, Indigenous representation, gender, student authorship and thematic research trends.

Results

We identified 128 publications written by 308 individual authors from 79 different organisations. Publications increased in number and diversity over each funding phase. During the final phase, publication outputs accelerated for organisations, students, project officers, Indigenous and female authors. Over time there was also a shift in research themes to encompass new clinical areas and social, environmental or behavioural determinants of health. Average degree (8.1), clustering (0.81) and diameter (3) indicated a well-connected network, with a core-periphery structure in each phase ($p \leq .03$) rather than a single central organisation (degree-centralisation=0.55-0.65). Academic organisations dominated the core structure in all funding phases.

Conclusion

Collaboration in publications increased with network consolidation and expansion. Increased productivity was associated with increased authorship diversity and a decentralised network, suggesting

these may be important factors in enhancing research impact and advancing the knowledge and practice of CQI in primary health care. Publication diversity and growth occurred mainly in the fourth phase, suggesting long-term relationship building among diverse partners is required to facilitate participatory research in CQI. Despite improvements, further work is needed to address inequities in female authorship and Indigenous authorship.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- A study strength was the long timeframe of 18 years of publications from an Australian quality improvement research network.
- To the best of our knowledge, this study is the first to describe a CQI research network using co-authorship network analysis
- Our analysis does not include the multiple affiliations of many of the authors and so may under-report the level of collaboration.
- Co-authorship is only one indicator of collaboration, though it has several advantages to relying on it as a proxy for assessing research collaboration including its verifiability, stability over time, and availability in the public domain.
- Many other collaborative efforts are not reflected in co-authorship metrics, such as collaborations that continue to occur through co-authorship, grant submissions, and conference presentations.

INTRODUCTION

Over the past two decades, continuous quality improvement (CQI) programs have been widely taken up by primary healthcare (PHC) services caring for Aboriginal and Torres Strait Islander people (hereafter respectfully referred to as Indigenous people, acknowledging their cultural and historical diversity) across Australia.(1, 2) CQI – a set of methods for improving the quality of care, through continuous measurement and problem-solving techniques(3, 4) – has been found to improve the quality of care delivered in Indigenous PHC.(1, 5)

While evidence indicates no single model of CQI outperforms others, the most successful applications of CQI are multi-site and multi-faceted approaches that aim to achieve change at various levels of the health system.(6) We and others have argued the need for multidisciplinary research networks to support the practice and effectiveness of CQI (6, 7) and to foster co-production and sharing of knowledge. However, despite research networks often being touted as a solution for enhancing knowledge translation into policy and practice, their characteristics and emergence over time are poorly understood.(8-10) Furthermore, evaluation challenges can be considerable because research networks are often loosely defined and manifest in different forms with formal and informal organisational structures.(11, 12)

We sought to better understand the development and growth of a multidisciplinary research network in Indigenous PHC quality improvement, and how these aspects reflected the vision of the network with respect to capacity strengthening, equity and membership diversity. Co-authorship network analysis offers one feasible strategy for evaluating the growth and emergence of research networks, because publications are well documented and reflect collaboration.(13-15) The study uses co-authorship network analysis to examine the growth and change in an 18-year CQI research network in Australian Indigenous primary health care. We address the question: How did the research network expand and change over time? Specifically we will investigate the extent to which the research network brought together people from a variety of organisations; the structural characteristics of the network; the level of equity in authorship relative to Indigenous status and gender; capacity strengthening efforts through examining student authorship; and changes in research themes over time.

The setting

Although Australia has a high-performing health system, underpinned by a universal health insurance scheme, it ranks low on measures of equity when compared with other Organisation for Economic Co-operation and Development (OECD) nations.(16) This ranking is reflected in consistent underperformance in addressing inequities in health care access, quality of care and outcomes for Indigenous people.(17-19) These inequities are underpinned by a legacy of colonisation, land

dispossession, displacement, disempowerment, social and economic exclusion, and ongoing racial discrimination.(19, 20)

To help address these inequities, the Audit and Best Practice in Chronic Disease (ABCD) participatory action research program was initiated in 2002. Drawing on international evidence about the effectiveness of system-wide CQI approaches to improve the quality of PHC service delivery,(21) the ABCD program employed a systems approach to support the CQI efforts of PHC services established to provide care for Indigenous Australians.(1, 6, 22) Connected to this research program, in 2010 a national, not-for-profit, CQI support entity – One21seventy – was established to support Indigenous PHC services in implementing CQI cycles using standardised, evidence-based, best practice clinical audit and systems assessment tools. Notably, 175 of the over 275 PHC centres involved provided the research network with de-identified data derived from their use of the CQI tools and processes. The studies published by network members reporting analyses of these data form a comprehensive picture of the quality of PHC received by Indigenous people around Australia. (1) Between 2010 and 2016, ABCD research accounted for 42 of the 60 (70%) peer-reviewed publications identified in a systematic review on CQI in Indigenous PHC in Australia,(2) and also made a significant contribution to international CQI research.(23) Importantly, although there were demonstrated improvements in quality of care in some areas of clinical care, there was continuing wide variation between PHC centres and jurisdictions.(1,5)

Table 1 sets out the four distinct phases of the ABCD program's evolution from 2002 to December 2019, its research aims, systems-strengthening dimensions and main findings. The intention of the resulting network was an 'open collaboration' that actively encourages cooperation with other organisations and individuals to help achieve the program's aims. The current phase of research (2020-24) is included in Table 1 but was not part of this study.

Table 1: Phases and research focus of the ABCD program, an action research project implementing quality improvement in Indigenous PHC, 2002–2019

	Phase 1 Exploring feasibility and acceptability of CQI tools and processes	**Phase 2** Exploring scalability and expansion of CQI	**Phase 3** Supporting wide-scale implementation of CQI and development of Partnership Learning Model		**Phase 4** Embedding CQI approaches in systems	Current Phase (not part of study) Strengthening leadership and engagement in system wide CQI
	ABCD (2002–2004)	**ABCD Extension (2005–2009)**	**ABCD National Research Partnership (2010–2014)**	**One21seventy (2010–2016) service support arm**	**Centre for Research Excellence in Integrated Quality Improvement (CRE-IQI) (2015–2019)**	Centre for Research Excellence in Strengthening Systems for Indigenous Health Care Equity (CRE-STRIDE) 2020–2024[#]
Research aims	Explore whether a CQI approach was feasible and effective in Indigenous PHC.(24)	Identify support requirements for large-scale implementation of the ABCD model.(25)	Understand variation in quality of care and strategies for improvement.(22)	Primarily a service support function. Voluntary contribution of data by services for research purposes, and potential for other involvement of services in research.	— Accelerate and strengthen large-scale CQI efforts. — Explore the feasibility/functioning of an 'innovation platform.'(26, 27)	— Strengthen Aboriginal and Torres Strait Islander research leadership for CQI. — Extend CQI methods to sectors beyond the PHC clinical environment.(28) — Enhance community participation in CQI processes.

Health system strengthening dimension	— Using participatory action research, a CQI process was introduced to 12 Indigenous PHC centres in one jurisdiction (Northern Territory) with a focus on the prevention and management of chronic disease.(29) — CQI approach embraced to improve (and demonstrate) quality of care. — Systems assessment tool provided a mechanism for ongoing local system improvement and integration with other organisations and sectors.(30)	— Geographic scope of the project was extended to include 69 Indigenous PHC services in several jurisdictions across Australia. — Scope was broadened to address other priority areas of PHC, with audit tools for additional areas of care. — Informed health system planning and policy by showing how the ABCD approach could be scaled up, and examined barriers/enablers to engagement and improvement.	— More than 175 Indigenous PHC services across Australia involved in ABCD program.(31) — Brought together stakeholders from across jurisdictions and levels of the health system to support and guide research on priority PHC health system issues, and to contribute to refining CQI tools and processes, interpreting data, applying findings and sharing lessons.(31)	Provided CQI training and tools with systems thinking focus, and web-based data analysis and reporting system able to provide local and aggregated data reports, with benchmarking. 275 + health services used ABCD tools and processes, and more than 2500 PHC staff were trained in the use of CQI tools and processes.(31)	— Adapted and extended the Partnership Learning Model, developed through previous phases of the research, by engaging with a wider range of stakeholders responsible for Indigenous PHC to solve problems and innovate together. — Emphasis on research capacity strengthening and research translation.(32)	— Develop new knowledge to strengthen integration in comprehensive PHC and embed CQI at all levels of the PHC system. — Strengthen Indigenous community input into improving CQI processes. — Extend CQI processes and collaborations across sectors.

Research findings	CQI approach was well accepted, demonstrated the feasibility and application of tools and processes, and showed improvements in care and intermediate health outcomes.	— Identified key barriers and enablers to scaling up in an Indigenous context.(33) — Established the need for further tools to support the implementation of CQI in Indigenous PHC.	— Demonstrated improvements in quality of care in some areas, and continuing wide variation between PHC centres and jurisdictions.(1,5) — Developed Partnership Learning Model to achieve large-scale improvements in quality of care and population health outcomes.(6)	— + 70% of PHC centres engaged in One21seventy provided their de-identified data to the ABCD National Research Partnership for use in research.	— Established that clinical and other areas such as community health promotion and prevention outcomes can be improved by using evidence-based CQI tools and processes.(34) — Identified factors that support the effective use of CQI by PHC teams and services, and improvements in delivery of care.(35) — Identified priorities for strengthening PHC systems to achieve large-scale health improvements.(36, 37)	Not applicable

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NB: ABCD – audit and best practice for chronic disease; CQI – continuous quality improvement; PHC – primary health care; NHMRC – National Health and Medical Research Council

Source: Adapted from Bailie et al. 2013

+ Although the projects were supported by research funding, it is important to note there were financial contributions and in-kind support from a range of community-controlled and government agencies.

CRE-STRIDE is the current form of the network, and its successful funding underscores the research program's longevity and stability.

METHODS

We used social network analysis, as described by Fonseca and co-authors(13) in their health sector co-authorship network analysis, to retrieve scientific publications, standardise entries for authors and organisations, visualise the network and calculate metrics.

Data retrieval

Details of peer-reviewed journal articles and books (the 'publications') were retrieved from administrative records held by the Centre for Research Excellence in Integrated Quality Improvement (CRE-IQI) coordinating centre, and included all publications published from 2002–2019.

Data categorisation, standardisation, and cleaning

Publications were sorted into categories and research themes that were iteratively developed and defined by JB and RSB. We describe the process for categorisation of included publications below.

Organisations: the affiliations of the authors (as per their citation on publications) were coded into Universities and Research Institutes; Government Departments; Health Services; Affiliates; Primary Health Networks; and Non-Government Organisations. Where authors had more than one affiliation listed on the publication, we used the first affiliation provided. Other key points in the categorisation of publications were as follows:

- We used the author's University rather than their specific Department and, if named, the Research Institute rather than the University.
- Where an author's affiliation was nominated as a hospital we used the State Health Department with which these organisations were affiliated.
- 'Affiliates' refers to regional support organisations established to support Indigenous health services, such as Aboriginal Medical Services Alliance Northern Territory.
- 'Health Service' refers to services established primarily to provide PHC to Indigenous people, and includes Aboriginal community-controlled services, Government services, and private General Practice.
- Primary Health Networks refer to independent regional PHC organisations across Australia that commission rather than provide services, as established by the Australian Government in July 2015.
- Non-Government Organisations refer to not-for-profit organisations that operate independently of Government, typically with the purpose of addressing a social or political issue.

Research themes*:* Publications were assigned to one of the following three research themes:

1. *CQI-related program activities that address clinical care delivery in the PHC setting:* publications that focus on the quality, and variations in delivery, of clinical care, and the application of, or learning from, CQI techniques in relation to a specific aspect of clinical care, e.g., child health and chronic illness care.
2. *CQI-related program activities that address social, environmental or behavioural determinants – i.e. community health promotion or prevention activities:* publications that focus on the application of, or learning from, CQI with a focus on areas such as health promotion, social and environmental conditions, housing, food security, and family wellbeing in general community settings.
3. *CQI-related processes and approaches:* publications related to CQI program development (such as study protocols and reviews informing CQI approaches), health systems strengthening, and the development and evaluation of research collaborations and their impact.

In categorising the publications by research themes, abstracts of publications were retrieved and screened by blinded reviewers (JB and RSB). Inconsistencies in reviewer assessments were resolved by consensus.

Role type: We identified all authors who were students or project officers at the time of the publication, and who had authored in this capacity. The student category included Public Health Trainees, and Masters, PhD, and Medical Honours students. Project officers were identified as those whose primary role supported research, and/or related either to health care administration and/or to project work.

Indigenous status*:* Coordinating centre records flagged authors who identified as Indigenous.

Gender: Authors were assigned a male or female category through a number of ways – reviewer knowledge of authors and Google searches.

Where there was uncertainty in allocating the above categories, JB checked with RSB and, when necessary, with the corresponding authors of the manuscripts. Data were entered into an Excel spreadsheet, and then standardised and cleaned by JB and BAP.

Network assembly, visualisation and analysis

The evolution of the research network was analysed over the four phases displayed in Table 1, with the analysis split into three parts: 1) an analysis of publications by type of organisation represented, research themes, the role of authors, and the Indigenous status of authors; 2) the network analysis of co-authorship between organisations; and 3) a core-periphery analysis of organisational position within the network.

Python programming language version 3.7.4(38) and the *Jupyter Notebook*(39) application accessed through the *Anaconda Navigator*(40) interface were used to script all data manipulation and analytical

work. Network analyses used the Python package *NetworkX*,(41) with visualisations produced with the open-source *Gephi* program.(42)

We first created a node list containing every organisation and its attributes (unique identifier, organisation name, type and years published), and an edge list representing co-authorship as pairwise combinations of each organisation listed on a publication and its unique attributes.

A single, undirected edge of weight=1 was assigned for each organisation pair that shared at least one publication in each phase of the network. For publications that involved only authors from the same organisation, a self-loop edge of weight=0 was assigned. No additional weight was given to the number of publications or authors involved or any other attribute. This approach was chosen so that results of the analysis could be directly interpreted in the context of inter-organisational collaboration.

Networks were analysed discretely across the four phases. Several network measures (defined in Table 2) were used to understand the resulting networks.

Table 2: Theoretical definitions of social network analysis measures, and their meaning in this study

Measure	**Definition, meaning in this study, and importance**
Node	The basic unit of a network. Nodes represent organisations. The node size is proportional to the number of publications.
Edge or Tie	An edge or tie connects two nodes in a network, and indicates a relationship between the two. An edge between two organisations indicates co-authorship of at least one publication.
Density	The density of a network is the total number of edges divided by the total number of possible edges. It is a widely used measure that reflects the level of cohesion among network organisations, or the extent to which organisations collaborated with every other organisation in the network.
Average degree	Degree is a count of the number of connections for any given node: the higher the average degree, the more connected the network. The average number of inter-organisational collaborations per organisation.
Clustering co-efficient	Clustering is a measure of how many of the nodes connected to a given node are also connected to each other, which is expressed as a proportion of the total possible connections. The overall clustering co-efficient is the average across the network. Where density tells you how connected the network is, the clustering co-efficient tells you how well connected the various neighbourhoods of the network are. A high clustering co-efficient and low density can be an indication of lots of small groups, loosely connected.

Path/path length	The path is any connected series of edges between two nodes. The length of a path is the number of steps (edges) and shows how quickly organisations can communicate with each other through their links.
Geodesic distance	The geodesic distance is the shortest path of all possible options between two nodes in the network. The number of steps it takes to get across a network is a useful measure of how quickly information can be disseminated to the entire network.
Diameter	The diameter of the network is the 'longest short path' between nodes and indicates the maximum number of steps it would take to get between nodes that are furthest away from each other in the network. The diameter gives a useful indication of how broad the network is.
Centralisation	This reflects how tightly the organisations are connected around the most central point of the network and how reliant the network may be on a central node.
Discrete core-periphery model	A network with a core-periphery structure has a 'core' of nodes densely connected to each other and to others, and 'periphery' nodes in the less-connected 'periphery' that are connected only to core nodes.

The analysis of network position at the organisational level uses discrete core-periphery analysis(43) to identify organisations that are well connected to each other (the core) as distinct from those less well connected (the periphery). To detect the core-periphery, we used the Borgatti and Everett(43) algorithm and the non-parametric statistical test devised by Kojaku and Masuda(44).

Patient and public involvement

No patients or members of the public were involved in the design, analysis or reporting of this study.

RESULTS

We identified 128 publications written by 308 authors, with a median of six authors per publication (Interquartile Range = 4–9.25), representing 79 different organisations (Table 3). Most authors (182 or 59.5%) contributed just one publication, while 18 (5.9%) contributed 10 or more. The chief investigator (RSB) of the original ABCD program co-authored 97 of the 128 publications (Supplementary File 1).

Table 3: Co-authorship characteristics, by phases and total 2002–2019

Indicator	Phase 1: 2002–2004	Phase 2: 2005–2009	Phase 3: 2010–2014	Phase 4: 2015–2019	Total: 2002–2019

Number of publications		2	15	21	90	128
Number of different authors		5	33	67	263	308
Number of authors per paper (median, IQR)		5, [5 - 5]	5, [3.5 - 8.5]	9, [4 - 13]	6, [5 - 9]	6, [4 - 9.25]
Organisational involvement						
Number of nodes (organisations)		3	12	24	72	79
Number and type of different organisations	University or Research Institute	3	8	15	45	48
	Government Department	–	2	3	9	10
	Affiliate	–	1	4	2	5
	Health Service	–	1	2	11	11
	Non-Government Organisation	–	–	–	4	4
	Primary Health Network	–	–	–	1	1
Number of publications with an author who has an international affiliation		0	1	0	8	9
Capacity strengthening						
Number and percentage of publications with a student/project officer as a lead author		0 (0%)	2 (13%)	3 (14%)	25 (28%)	30 (23%)
Number and percentage of publications with at least one student/project officer as an author		2 (100%)	12 (80%)	13 (62%)	52 (58%)	79 (62%)
Addressing equity						
Number and percentage of female authors		1 (25%)	20 (60%)	39 (58%)	171 (65%)	192 (62%)
Number and percentage of publications with a female first author		0 (0%)	2 (13%)	14 (67%)	76 (84%)	92 (72%)
Number and percentage of publications with a female last author		0 (0%)	4 (27%)	6 (29%)	25 (28%)	35 (27%)
Number and percentage of publications with at least one Indigenous author		0 (0%)	6 (40%)	13 (62%)	56 (62%)	75 (59%)
Number and percentage of publications with an Indigenous lead author		0 (0%)	0 (0%)	2 (10%)	3 (3%)	5 (4%)
Number and percentage of publications with an Indigenous last author		0 (0%)	3 (20%)	0 (0%)	0 (0%)	0 (0%)
Thematic trends in publications						

Thematic areas, number and percentage	CQI-related activities in clinical care	2 (100%)	6 (40%)	8 (38%)	44 (49%)	60 (47%)
	CQI activities in areas such as community-based health promotion and prevention	0	2 (13%)	5 (24%)	16 (18%)	23 (18%)
	Processes and approaches for CQI	0	7 (47%)	8 (38%)	30 (33%)	45 (35%)
Co-authorship network structural characteristics						
Density		1	0.45	0.47	0.11	0.13
Average degree (organisations)		2	5	10.9	8.1	9.8
Centralisation (degree)		0	0.65	0.57	0.55	0.53
Clustering		1	0.80	0.86	0.81	0.79
Geodesic distance		1	1.5	1.5	2.1	2.1
Diameter		1	2	2	3	3
Core-periphery structure		0	1 (p=.03)	1 (p=.01)	1 (p<.001)	0.42 (p=.83)

CQI: continuous quality improvement; IQR: interquartile range

Linking people from a variety of organisations

As shown in Table 3, there was an increase in the number and type of different organisations in the network, with considerable growth from Phase 3 (24 organisations) to Phase 4 (72 organisations). Of note, the number of Universities and Research Institutes increased from 15 in Phase 3 to 45 in Phase 4, while Health Services rose from 2 to 11 and international organisations increased to 8. This growth in different organisations participating in the research network over time was a result of existing organisations continuing to publish together (yellow nodes), and new organisations co-authoring (blue nodes) (Figure 1). A few organisations ceased publishing as part of the network (red nodes), shown as 'isolates'.

[INSERT FIGURE 1]

Figure 1: Evolution of the quality improvement research network, 2002–2019

Relationships of organisations and structural characteristics

The structural characteristics of the networks are based on the indicators shown in Table 3. Our analysis of the network data shows a decrease in the network density. In Phase 2 and 3, the research network was relatively well connected with ~46% of all possible relationships in the network actualised. However, in Phase 4, with ~11% of all possible links existing between organisations, there was less connectivity between organisations. The decrease in network density was linked to an increase in the

number of organisations publishing together in Phase 4, as noted above (Table 3), and an increase in the scope of CQI publications. However, the average clustering coefficient remained high across all phases (1, 0.80, 0.86, and 0.81 respectively), indicating a strong tendency for multiple organisations to be collaborating on individual publications. Part of this high effect is a natural consequence of authors publishing together – it introduces triangles of collaborating authors, thereby increasing the clustering co-efficient.

From Table 3, we note that the average number of organisations collaborating directly on publications (average node degree) steadily increased from 2 in Phase 1, to 5, 10.9, and then 8.1 in subsequent phases. This is a sign that organisations collaborated more widely over time, with a small decrease in Phase 4. On average, publications involved 3.4 organisations, with 3.5 publications per organisation. This indicates a maturation of organisational relationships, typically creating more than one publication from each collaboration. Furthermore, network diameter was at-most 3 (Phase 4) and geodesic distance was at-most 2.1 (Phase 4). This indicates a close-knit cohesive network in which organisations were connected by no more than two other organisations, resulting in the network being unlikely to fragment and able to disseminate information quickly.

The degree-centralisation from Phase 2 was 0.65 followed by 0.57 and 0.55 in the subsequent phases. Conversely, the core-periphery analysis produced strong results in each phase (see Table 3). These analyses indicate that in all four phases the network was not connected via a single dominant central organisation but rather by a core-periphery structure that points to a more collaborative network. Intersectoral collaboration (research, government and/or health services) were represented in the core for phases 2 and 3 (green nodes in Figure 2). In Phase 4, the organisations comprising the core were all Universities or Research Institutes, indicating that Government Departments and Health Services were more likely to publish with them than with each other.

[INSERT FIGURE 2]

Figure 2: Core periphery analysis by phases, 2002–2019

Equity in authorship

Female first authors increased over time, growing from none in Phase 1 to 84% (n=76) in Phase 4 (Table 3), with about 28% of the publications having a female senior or last author in all phases after the first. Although the number of publications led by Indigenous authors remained low, over time there was an increasing number and percentage with at least one Indigenous author. The greatest expansion was observed from Phase 3 to Phase 4 when the number of publications with at least one Indigenous author increased from 13 to 56 (Table 3).

Providing opportunities for capacity strengthening

Over time there was also an increase in absolute number (but a decline in percentage) of publications with at least one student or project officer author, from 2 in Phase 1 to 52 in Phase 4 (Table 3). Phase 4 also saw an increase in student or project officer as lead author, with the largest growth in Phase 4 (28%, n=25) representing a two-fold increase from Phase 3 (14%, n=3).

Expansion of research themes

As the network evolved there was a notable growth in publications related to CQI and clinical care, an increase in publications related to social, environmental and behavioural determinants of health, and on the development of processes and approaches for CQI (Table 3). The growth in research themes in Phase 4 was consistent with the increase observed in the number of publications and organisations involved in this phase, and the emergence of new core organisations. Supplementary File 2 contains a listing of all publications and their assigned category of research themes.

DISCUSSION

This study examined the growth of and changes in an Australian quality improvement research network over an 18-year period by assessing co-authorship of publications using network analysis. Key findings include an expansion in the number of publications; a greater number and diversity of organisations co-authoring; improvements in capacity strengthening measures reflected in increased student and project officer authorship and first author position; and a broadening or scaling-out(45) of quality improvement work to other thematic areas. There is evidence, too, that the research network linked people from a variety of organisations, including Universities or Research Institutes, PHC services and Government Departments, who might otherwise have never worked together. This expansion potentially extended both the impact of the network and of the organisations involved.

The characteristics of the network showed a strong collaborative structure and a maturation of organisational relationships, with more than one publication typically developed by each collaborating organisation. Network analyses indicated a core-periphery structure of organisations connected to each other in each phase, rather than a network structured around a single central organisation. As there was the same Chief Investigator throughout the study period, this finding of a core-periphery structure indicates the network expanded to have other core organisations over time, and was not just centred on the Chief Investigators organisation. In phases 2 and 3, the relationships between research institutions and government departments were well represented in the network core. The network's founding partners maintained a consistent presence as members of the core, indicating that it remained dependent on these partners for collaboration. However, new core organisations emerged when key authors changed institutions, reflecting that individuals stimulated the expansion of core members. For example, a result of key individuals moving institutions and growing the publishing base was a Phase 4 core comprised solely of Universities and Research Institutes, while Health Service and Government

Organisations were part of the core in the earlier phases. This change occurred despite a large increase in the number and type of organisations involved in the network in Phase 4.

Network growth was greatest in Phase 4, when funding was received from the Australian Government's NHMRC to establish a Centre for Research Excellence and the network's structure and function(12) evolved to that of an 'innovation platform.'(26) Used as a vehicle to stimulate and support multi-stakeholder collaboration and learning, 'innovation platforms' provide a space of interaction to facilitate the development and emergence of innovations when there are complex, system-wide issues requiring coordinated action and collective problem solving. Most extensively applied in international agricultural development, and to a limited extent in health, innovation platforms differ from other networks by the incorporation of a wider network of stakeholders at multiple levels of the system and in different roles; the concept of "sector boundary spanning" that brings in stakeholders from other sectors to assist in developing health care solutions; and application of continuous reflection, learning and adaptation as central design elements.(26, 27)

These findings support previous literature that researchers tend to collaborate with like-minded others, but that this tendency toward homophily can be disrupted by implementing policies that encourage interdisciplinary collaboration and purposeful research translation – such as was done with the innovation platform.(14) Although the purposeful adjustment to an 'innovation platform' was associated with an expansion of activity among the network and new thematic scope in publications, this acceleration could also reflect other inter-related factors, such as longer-term relationships, and an increase in funding.

Furthermore, the earlier phases were focused on supporting PHC services to implement and embed quality improvement techniques through participatory action research. Access to the CQI dataset formed the basis of research collaborations between those services and University and Research Institutes to undertake data analyses that resulted in publications up to 2019. Though there were 175 PHC services providing data to the research collaboration, only 11 Health Services co-authored publications. While not necessarily co-authors, Health Services made important contributions to implementing research, collecting data, and importantly – to interpretation and analysis of findings.

Our findings build on a prior social network analysis of partners in the research network which was undertaken as part of an interim evaluation in Phase 3 of the research network. Cunningham and her co-authors(46) found an increase in network density (43% to 59%) from 2013 to 2014, indicating an increase over time in connectivity and communication between partner organisations. A major element in achieving the goals of that phase of research was the network's focus on developing a shared database of de-identified CQI data from Indigenous PHC centres.(46) The importance to the research network of collecting and sharing data is supported by the experiences of other research collaborations.(47, 48) Furthermore, the high level of trust identified across the network is indicative of a properly functioning

collaboration.(49) The growth in Phase 4 leveraged the high level of trust already established. The decreasing degree of centralisation scores are consistent with findings reported by Cunningham et al.(46), and reflect the shift towards more organisations taking a greater role in publishing. Increasing the number of diverse collaborations and creating a more decentralised network has been shown to improve productivity and increase the potential for high-impact science.(50)

Equity and capacity strengthening are promoted as core elements of research networks.(12, 51) The research network, particularly when operating as an innovation platform, made some progress in addressing concerns about the imbalances between Indigenous and non-Indigenous authors when writing about Indigenous issues. However, despite an increased number of publications with Indigenous authors, especially in Phase 4, there remains a paucity of Indigenous first or senior/last authors. Further work is needed to redress the inequities these imbalances represent, a concern echoed in global health literature.(52) The latest iteration of the research network was recently launched with funding for a new Centre for Research Excellence in Strengthening Systems for Indigenous Health Care Equity (2020–2024) (CRE-STRIDE) (NHMRC Grant Id #1170882). This Centre marks the beginning of a new Indigenous leadership structure for the research network with more than half of the research investigators, including the Chief Investigator, identifying as Indigenous. It also aims to extend and further support the use of CQI methods in sectors with responsibility for addressing social and cultural determinants of health and to enhance community participation in CQI processes.(28)

Strengths and limitations of the study

A study strength was the long timeframe of 18 years of publications. Although co-authorship is only one indicator of collaboration, there are several advantages to relying on it as a proxy for assessing the level of research collaboration, including its verifiability, stability over time, availability of data in the public domain and ease of measurement.(11)

As the aim of the study was to assess growth and change in the research collaboration over time, we applied an unweighted method to the network analysis. This approach was chosen for a number of reasons. Firstly, the interpretability would be compromised by weighting edges, in the context of the questions we wished to answer. We moved all of the information that would have otherwise been embedded into a weight to separate descriptive analyses available in Table 3. Secondly, given the temporal nature of collaborations we did not wish to make erroneous assumptions that quantity of publications is a substitute for quality. For example, it is difficult to compare a collaboration that generates only one high impact publication to a collaboration that may produce a larger number of lower impact publications. Weighting by publication numbers could therefore introduce a bias that may lead to erroneous interpretation of the findings.

Limitations of this study include: 1) many collaborative efforts are not reflected in co-authorship metrics. We are undertaking other studies to address this as part of the overall evaluation of the CRE-IQI. Other measures of collaborative ties include having co-investigators on submitted or funded grants, on conference presentations and as authors of grey literature, all of which may be useful to broaden the definition of collaboration in our innovation platform. However, we assumed that, in most cases, co-authorship indicates an active cooperation between partners beyond the simple exchange of material or information. 2) This analysis does not capture the collaborations that continue to occur through co-authorship or other means that are not necessarily related to the research network. For example, a collaboration formed by co-authoring on a CRE-IQI manuscript might lead to collaboration on other projects and research not reflected in this analysis. 3) Because there is a substantial lead-time for an academic publication, a writing collaboration that might have commenced in an earlier phase of work may not have been published until a later phase. Thus publication in one phase can arise from substantial work in a previous phase. 4) Although multiple authorship affiliations are increasingly recognised as facilitating knowledge exchange and becoming more widespread,(53) our analysis does not include the multiple affiliations of many of the authors and so may under-report the level of collaboration. Similarly, only representing the University affiliation, and not the actual Department in which an author works, obscures collaboration between Departments in the same University. 5) Three of the eleven authors on this manuscript (RSB, JB and VM) had published more than 20 manuscripts included in this analysis, and RSB was the Chief Investigator on the research network during this period. Given this, and to mitigate against bias, BAP who has not published as part of this network undertook the network analysis and a blind review process for categorising the manuscripts, with discrepancies discussed.

To the best of our knowledge, this study is the first to describe a CQI research network using co-authorship network analysis. While the generalisability of the findings may be limited to similar networks, the methodological approach could readily be transferred. In this study we did not set out to demonstrate a link between an expansion of the collaboration and engagement with impact or improvement in the quality of care. However, it is widely recognised in the literature, that increasing collaboration and engagement across health services, researchers and policy makers is a critically important element along the causal change pathway to improving the quality of care and achieving impact. Methods such as co-authorship analysis are useful for demonstrating a pathway to research impact related to engagement, which traditionally tends to rely on the quantity of outputs rather than on the strengthening of networks and the scope of work undertaken.

CONCLUSION

Over the 18-year timeframe, collaboration in publications increased with network consolidation and expansion. Publication outputs accelerated in the final phase, coinciding with a broader thematic focus

and an increase in the number and diversity of participating organisations. This expansion occurred largely due to the cumulative effect of building trust and relationships over time, including the development of a comprehensive dataset for use by all stakeholders. The findings highlight the benefits of long-term relationship building among diverse partners to support participatory research in quality improvement. Increased productivity was associated with increased authorship diversity and a decentralised network, suggesting these may be important factors in enhancing research impact and advancing the knowledge and practice of CQI in primary health care. Despite improvements, further work is needed to address inequities in female authorship and Indigenous authorship. The co-authorship analysis has been useful for demonstrating research impacts related to collaboration, which are not well captured by metrics such as quantity of outputs.

Declarations

Ethics approval: University of Sydney Human Research Ethics Committee (Project 2018/206) and the Human Research Ethics Committee of the Northern Territory Department of Health and Menzies School of Health Research (Project 2018-3105).

Consent for publication: Not applicable

Availability of data and material: The data set is available from the corresponding author on reasonable request and if consistent with the projects' ethics approvals.

Competing interests: The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Author's information: RSB was the Chief Investigator of the research network from 2002 – 2019. RSB, JB, VM, AL, FCC, RGB, and AL had published 5 or more publications as part of this research network. RGB and VM are both Indigenous researchers: RGB is from the Gungarri/Kunja nations in South-Western Queensland and VM from the Quandamooka community on North Stradbroke Island, Queensland. JB, BAP, RSB, DP, AL, SA, KPC, MEP and FCC are non-Indigenous researchers. All authors have a long-standing commitment to improving health outcomes for Aboriginal and Torres Strait Islander people.

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Formal analysis: JB, BAP.
Data interpretation: JB, BAP, AL, SA, RSB, FCC, VM, RGB, KPC, MEP, DP
Funding acquisition: JB, RSB.
Methodology: JB, BAP, FCC, RSB.
Project administration: JB
Supervision: DP, FCC.
Visualization: BAP, JB.
Writing – original draft: JB, BAP.
Writing – critical intellectual input & editing: JB, BAP, AL, SA, RSB, FCC, VM, RGB, KPC, MEP, DP.

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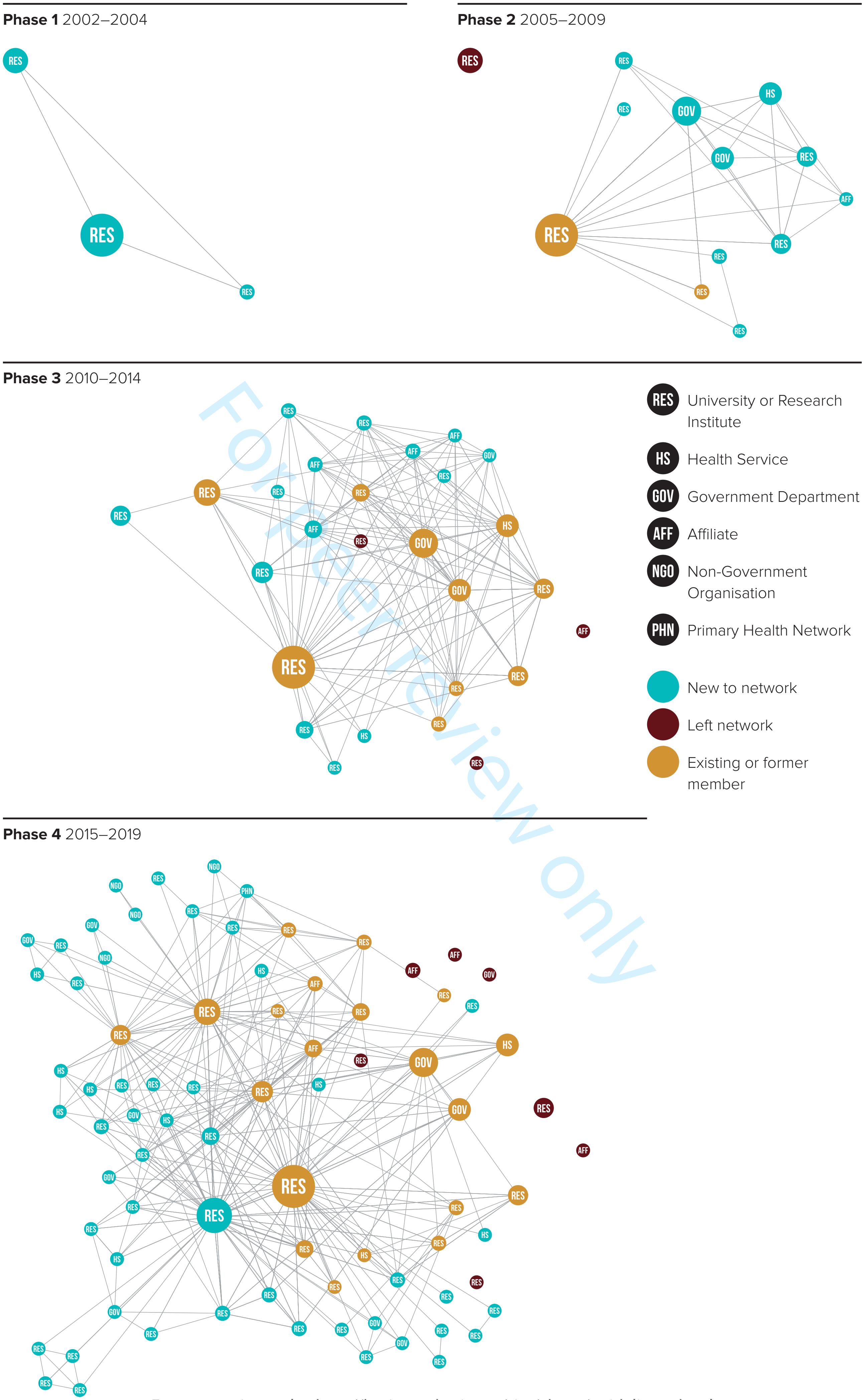

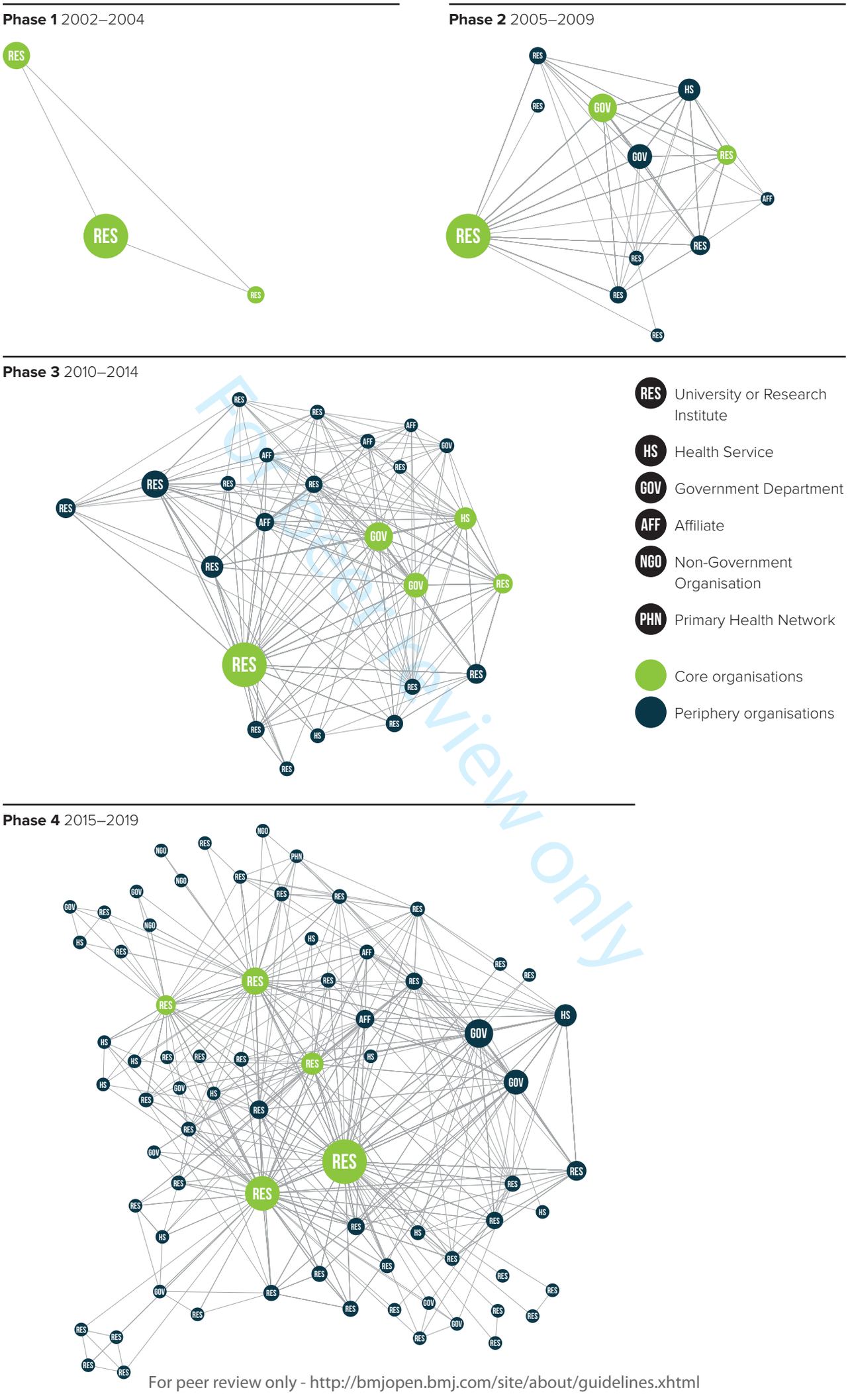

SUPPLEMENTARY FILE 1

Table S1: Total number of publications, per author, for those who have published 5 or more as part of the research collaboration, 2002–2019

Author name (last_first)	Total number of publications
Bailie_Ross	97
Matthews_Veronica	36
Thompson_Sandra	21
Tsey_Komla	21
Bailie_Jodie	21
Si_Damin	20
Connors_Christine	20
Dowden_Michelle	17
O'Donoghue_Lynette	15
Weeramanthri_Tarun	14
Larkins_Sarah	13
Kennedy_Catherine	12
Schierhout_Gill	12
Cunningham_Frances	12
Clelland (Percival)_Nikki	11
Laycock_Alison	11
Kwedza_Ru	10
Bainbridge_Roxanne	10
Cox_Rhonda	9
Brown_Alex	9
McCalman_Janya	9
Robinson_Gary	8
Liddle_Helen	8
Burke_Hugh	8
Rumbold_Alice	7
Boyle_Jacqueline	7
Gardner_Karen	6
Ralph_Anna	6
Burgess_Paul	6
Nagel_Tricia	5
Moore_Elizabeth	5

Doran_Chris	5
Garvey_Gail	5
Valery_Patricia	5
Kinchin_Irina	5
McAullay_Dan	5
McAuley_Kimberley	5
Strobel_Natalie	5
Edmond_Karen	5
Onnis_Leigh-Ann	5

SUPPLEMENTARY FILE 2

Table S1: Publications included in the analysis, phase and research theme allocation, 2002–2019

	Phases of research collaboration				Categories of research themes		
	Phase 1: 2002 – 2004	Phase 2: 2005 – 2009	Phase 3: 2010 – 2014	Phase 4: 2015 – 2019	CQI in PHC Clinical care	CQI activities in social, environmental or behavioural determinants	Processes and approached for CQI
Bailie RS, Togni SJ, Si D, et al. Preventive medical care in remote Aboriginal communities in the Northern Territory: a follow-up study of the impact of clinical guidelines, computerised recall and reminder systems, and audit and feedback. *BMC Health Serv Res* 2003;3(1):15.	1				1		
Bailie RS, Si D, Togni SJ, et al. A multifaceted health-service intervention in remote Aboriginal communities: 3-year follow-up of the impact on diabetes care. *MJA* 2004;181(4):195–200.	1				1		
Si D, Bailie R, Connors C, et al. Assessing health centre systems for guiding improvement in diabetes care. *BMC Health Serv Res* 2005;5(1):56.		1			1		
Wayte KJ, Bailie RS, Stephenson P. Improving the feedback of housing information to Indigenous communities. *Environmental Health* 2005;5(2):36.		1				1	
Bailie RS, Wayte KJ. A continuous quality improvement approach to Indigenous housing and health. *Environmental Health* 2006;6(2):36–41.		1				1	
Bailie RS, Robinson G, Kondalsamy-Chennakesavan SN, et al. Investigating the sustainability of outcomes in a chronic disease treatment programme. *Soc Sci Med* 2006;63(6):1661–70.		1			1		
Bailie R, Si D, Dowden M, et al. Improving organisational systems for diabetes care in Australian Indigenous communities. *BMC Health Serv Res* 2007;7(1):67.		1			1		
Bailie RS, Si D, O'Donoghue L, et al. Indigenous health: effective and sustainable health services through continuous quality improvement. *MJA* 2007;186(10):525–7.		1					1
Si D, Bailie RS, Dowden M, et al. Delivery of preventive health services to Indigenous adults: response to a systems-oriented primary care quality improvement intervention. *MJA* 2007;187(8):453–7.		1			1		

McDonald EL, Bailie RS, Rumbold AR, et al. Preventing growth faltering among Australian Indigenous children: implications for policy and practice. *MJA* 2008;188:S84–S6.		1					1
Bailie RS, Si D, Dowden MC, et al. Delivery of child health services in Indigenous communities: implications for the federal government's emergency intervention in the Northern Territory. *MJA*. 2008;188(10):615–8.		1			1		
Si D, Bailie R, Cunningham J, et al. Describing and analysing primary health care system support for chronic illness care in Indigenous communities in Australia's Northern Territory – use of the Chronic Care Model. *BMC Health Serv Res* 2008;8(1):112.		1					1
Bailie R, Sibthorpe B, Gardner K, et al. Quality improvement in Indigenous primary health care: history, current initiatives and future directors. *Aust J Prim Health* 2008;14(2):53–7.		1					1
Bailie R, Si D, Connors C, et al. Study protocol: audit and best practice for chronic disease extension (ABCDE) project. *BMC Health Serv Res* 2008;8(1):184.		1					1
Si D, Bailie R, Weeramanthri T. Effectiveness of chronic care model-oriented interventions to improve quality of diabetes care: a systematic review. *Prim Health Care Res Dev* 2008;9(1):25–40.		1					1
Bailie RS, Si D, Dowden MC, et al. A systems approach to improving timeliness of immunisation. *Vaccine* 2009;27(27):3669–74.		1			1		
Baeza J, Bailie R, Lewis JM. Care for chronic conditions for indigenous Australians: key informants' perspectives on policy. *Health Policy* 2009;92(2–3):211–7.		1					1
Si D, Bailie R, Dowden M, et al. Assessing quality of diabetes care and its variation in Aboriginal community health centres in Australia. *Diabetes/Metabolism Research and Reviews* 2010;26(6):464–73.			1		1		
McDonald E, Bailie R, Grace J, et al. An ecological approach to health promotion in remote Australian Aboriginal communities. *Health Promot Int* 2010;25(1):42–53.			1			1	
Rumbold AR, Bailie RS, Si D, et al. Assessing the quality of maternal health care in Indigenous primary care services. *MJA* 2010;192(10):597.			1		1		
Si D, Bailie R, Wang Z, Weeramanthri T. Comparison of diabetes management in five countries for general and indigenous populations: an internet-based review. *BMC Health Serv Res* 2010;10(1):169.			1				1
Gardner KL, Dowden M, Togni S, Bailie R. Understanding uptake of continuous quality improvement in Indigenous primary health care: lessons from a multi-site case study of the Audit and Best Practice for Chronic Disease project. *Implement Sci* 2010;5(1):21.			1				1

Bailie R, Si D, Shannon C, Semmens J, et al. Study protocol: national research partnership to improve primary health care performance and outcomes for Indigenous peoples. *BMC Health Serv Res* 2010;10(1):129.			1				1
Gardner K, Bailie R, Si D, et al. Reorienting primary health care for addressing chronic conditions in remote Australia and the South Pacific: review of evidence and lessons from an innovative quality improvement process. *Aust J Rural Health* 2011;19(3):111–7.			1				1
Rumbold AR, Bailie RS, Si D, et al. Delivery of maternal health care in Indigenous primary care services: baseline data for an ongoing quality improvement initiative. *BMC Pregnancy Childbirth* 2011;11(1):16.			1		1		
Bailie RS, Si D, Connors CM, et al. Variation in quality of preventive care for well adults in Indigenous community health centres in Australia. *BMC Health Serv Res* 2011;11(1):139.			1		1		
Si D, Dowden M, Kennedy C, Cox R, et al. Indigenous community care: documented depression in patients with diabetes. *Aust Fam Physician* 2011;40(5):331.			1		1		
Gausia K, Thompson S, Nagel T, et al. Antenatal emotional wellbeing screening in Aboriginal and Torres Strait Islander primary health care services in Australia. *Contemp Nurse* 2013;46(1):73–82.			1		1		
Ralph AP, Fittock M, Schultz R, et al. Improvement in rheumatic fever and rheumatic heart disease management and prevention using a health centre-based continuous quality improvement approach. *BMC Health Serv Res* 2013;13(1):525.			1		1		
Bailie R, Matthews V, Brands J, et al. A systems-based partnership learning model for strengthening primary healthcare. *Implement Sci* 2013;8(1):143.			1				1
Schierhout G, Hains J, Si D, et al. Evaluating the effectiveness of a multifaceted, multilevel continuous quality improvement program in primary health care: developing a realist theory of change. *Implement Sci* 2013;8(1):119.			1				1
Schierhout G, Nagel T, Si D, et al. Do competing demands of physical illness in type 2 diabetes influence depression screening, documentation and management in primary care: a cross-sectional analytic study in Aboriginal and Torres Strait Islander primary health care settings. *Int J Ment Health Syst* 2013;7(1):16.			1				1
McDonald EL, Bailie R, Michel T. Development and trialling of a tool to support a systems approach to improve social determinants of health in rural and remote Australian communities: the healthy community assessment tool. *Int J Equity Health* 2013;12(1):15.			1			1	

O'Donoghue L, Percival N, Laycock A, et al. Evaluating Aboriginal and Torres Strait Islander health promotion activities using audit and feedback. *Aust J Prim Health* 2014;20(4):339–44.			1			1	
Bailie R, Bailie J, Chakraborty A, et al. Consistency of denominator data in electronic health records in Australian primary healthcare services: enhancing data quality. *Aust J Prim Health* 2015;21(4):450–9.			1				1
Matthews V, Schierhout G, McBroom J, et al. Duration of participation in continuous quality improvement: a key factor explaining improved delivery of Type 2 diabetes services. *BMC Health Serv Res* 2014;14(1):578.			1		1		
Brimblecombe J, Van Den Boogaard C, Ritchie J, et al. From targets to ripples: tracing the process of developing a community capacity building appraisal tool with remote Australian indigenous communities to tackle food security. *BMC Public Health* 2014;14(1):914.			1			1	
McDonald EL, Bailie RS, Morris PS. Participatory systems approach to health improvement in Australian Aboriginal children. *Health Promot Int* 2017;32(1):62–72.			1			1	
Gausia K, Thompson SC, Nagel T, et al. Risk of antenatal psychosocial distress in indigenous women and its management at primary health care centres in Australia. *General Hospital Psychiatry* 2015;37(4):335–9.				1	1		
Puszka S, Nagel T, Matthews V, et al. Monitoring and assessing the quality of care for youth: developing an audit tool using an expert consensus approach. *Int J Ment Health Syst* 2015;9(1).				1	1		
Gibson-Helm ME, Teede HJ, Rumbold AR, et al. Continuous quality improvement and metabolic screening during pregnancy at primary health centres attended by Aboriginal and Torres Strait Islander women. *MJA* 2015;203(9):369–70.				1	1		
Tretheway R, Taylor J, O'Hara L, Percival N. A missing ethical competency? A review of critical reflection in health promotion. *Health Promot J Austr* 2015;26(3):216–21.				1		1	
McCalman J, Bainbridge R, Russo S, et al. Psycho-social resilience, vulnerability and suicide prevention: impact evaluation of a mentoring approach to modify suicide risk for remote Indigenous Australian students at boarding school. (Report). *BMC Public Health* 2016;16(108).				1		1	
Newham J, Schierhout G, Bailie R, et al. 'There's only one enabler; come up, help us': staff perspectives of barriers and enablers to continuous quality improvement in Aboriginal primary health-care settings in South Australia. *Aust J Prim Health* 2016;22(3):244–54.				1			1

Larkins S, Woods CE, Matthews V, et al. Responses of Aboriginal and Torres Strait Islander primary health-care services to continuous quality improvement initiatives. *Front Public Health* 2016;3:288.				1	1		
Crinall B, Boyle J, Gibson-Helm M, et al. Cardiovascular disease risk in young Indigenous Australians: a snapshot of current preventive health care. *Aust N Z J Public Health* 2017;41(5):460–6.				1	1		
Bailie C, Matthews V, Bailie J, et al. Determinants and gaps in preventive care delivery for Indigenous Australians: a cross-sectional analysis. *Front Public Health* 2016;4.				1	1		
Ralph AP, de Dassel JL, Kirby A, et al. Improving delivery of secondary prophylaxis for rheumatic heart disease in a high-burden setting: outcome of a stepped-wedge, community, randomized trial. *J Am Heart Assoc: Cardiovascular and Cerebrovascular Disease* 2018;7(14).				1	1		
Vasant BR, Matthews V, Burgess CP, et al. Wide variation in absolute cardiovascular risk assessment in Aboriginal and Torres Strait Islander people with Type 2 diabetes. *Front Public Health* 2016;4:37.				1	1		
Percival N, O'Donoghue L, Lin V, et al. Improving health promotion using quality improvement techniques in Australian Indigenous primary health care. *Front Public Health* 2016;4.				1		1	
Laycock A, Bailie J, Matthews V, et al. Interactive dissemination: engaging stakeholders in the use of aggregated quality improvement data for system-wide change in Australian Indigenous primary health care. *Front Public Health* 2016;4.				1			1
Bailie J, Laycock A, Matthews V, et al. System-level action required for wide-scale improvement in quality of primary health care: synthesis of feedback from an interactive process to promote dissemination and use of aggregated quality of care data. *Front Public Health* 2016;4.				1	1		
Gibson-Helm M, Rumbold A, Teede H, et al. Improving the provision of pregnancy care for Aboriginal and Torres Strait Islander women: a continuous quality improvement initiative. *BMC Pregnancy Childbirth* 2016;16(118).				1	1		
Percival NA, McCalman J, Armit C, et al. Implementing health promotion tools in Australian Indigenous primary health care. *Health Promot Int* 2018;33(1):92–106.				1		1	
Hayward MN, Paquette-Warren J, Harris SB. Developing community-driven quality improvement initiatives to enhance chronic disease care in Indigenous communities in Canada: the FORGE AHEAD program protocol. *Health Res Policy Syst* 2016;14(1):55.				1			1

D'Aprano A, Silburn S, Johnston V, et al. Challenges in monitoring the development of young children in remote Aboriginal health services: clinical audit findings and recommendations for improving practice. *Rural Remote Health* 2016;16(3):3852.				1	1		
Cunningham FC, Ferguson-Hill S, Matthews V, et al. Leveraging quality improvement through use of the Systems Assessment Tool in Indigenous primary health care services: a mixed methods study. *BMC Health Serv Res*. 2016;16(1).				1			1
Schierhout G, Matthews V, Connors C, et al. Improvement in delivery of type 2 diabetes services differs by mode of care: a retrospective longitudinal analysis in the Aboriginal and Torres Strait Islander primary health care setting. *BMC Health Serv Res* 2016;16(1):560.				1	1		
Burnett AM, Morse A, Naduvilath T, et al. Delivery of eye and vision services in Aboriginal and Torres Strait Islander primary healthcare centers. *Front Public Health* 2016;4.				1	1		
Searles A, Doran C, Attia J, et al. An approach to measuring and encouraging research translation and research impact. *Health Res Policy Syst* 2016;14(1).				1			1
Doran CM, Ling R, Searles A, et al. Does evidence influence policy? Resource allocation and the Indigenous Burden of Disease Study. *Aust Health Rev* 2016;40(6):705–15.				1			1
McCalman J, Bainbridge R, Percival N, et al. The effectiveness of implementation in Indigenous Australian healthcare: an overview of literature reviews. *Int J Equity Health* 2016;15:47.				1			1
Woods C, Carlisle K, Larkins S, et al. Exploring systems that support good clinical care in Indigenous primary health-care services: a retrospective analysis of longitudinal systems assessment tool data from high-improving services. *Front Public Health* 2017;5(45).				1			1
Hayward MN, Mequanint S, Paquette-Warren J, et al. The FORGE AHEAD clinical readiness consultation tool: a validated tool to assess clinical readiness for chronic disease care mobilization in Canada's First Nations. *BMC Health Serv Res* 2017;17(1).				1			1
Kearns T, Ward F, Puszka S, et al. Anaemia health literacy of community members and health practitioners knowledge of best practice guidelines in a remote Australian Aboriginal community. *Univers J Public Health* 2017;5(1):32–9.				1	1		
Nattabi B, Matthews V, Bailie J, et al. Wide variation in sexually transmitted infection testing and counselling at Aboriginal primary health care centres in Australia: analysis of longitudinal continuous quality improvement data. *BMC Infect Dis* 2017;17(1).				1	1		

Meiklejohn JA, Garvey G, Bailie R, et al. Follow-up cancer care: perspectives of Aboriginal and Torres Strait Islander cancer survivors. *Support Care Cancer* 2017;25(5):1597.				1	1		
Laycock A, Bailie J, Matthews V, et al. A developmental evaluation to enhance stakeholder engagement in a wide-scale interactive project disseminating quality improvement data: study protocol for a mixed-methods study. *BMJ Open* 2017;7(7).				1			1
Bailie J, Matthews V, Laycock A, et al. Improving preventive health care in Aboriginal and Torres Strait Islander primary care settings. *Globalization and Health* 2017;13(1):48.				1	1		
Brimblecombe J, Bailie R, van Den Boogaard C, et al. Feasibility of a novel participatory multi-sector continuous improvement approach to enhance food security in remote Indigenous Australian communities. *SSM – Popul Health* 2017;3(C):566–76.				1		1	
Langham E, McCalman J, Matthews V, et al. Social and emotional wellbeing screening for Aboriginal and Torres Strait Islanders within primary health care: a series of missed opportunities? *Front Public Health* 2017;5:159.				1	1		
de Witt A, Cunningham FC, Bailie R, Bernardes CM, Matthews V, Arley B, et al. Identification of Australian Aboriginal and Torres Strait Islander cancer patients in the primary health care setting. *Front Public Health* 2017;5:199.				1	1		
Matthews V, Burgess CP, Connors C, et al. Integrated clinical decision support systems promote absolute cardiovascular risk assessment: an important primary prevention measure in Aboriginal and Torres Strait Islander primary health care. *Front Public Health* 2017;5(233).				1	1		
Bailie R, Matthews V, Larkins S, et al. Impact of policy support on uptake of evidence-based continuous quality improvement activities and the quality of care for Indigenous Australians: a comparative case study. *BMJ Open* 2017;7(10).				1			1
Zuchowski I, Miles D, Woods C, Tsey K. Continuous quality improvement processes in child protection: a systematic literature review. *Res Soc Work Pract* 2017:1049731517743337.				1		1	
Ramanathan S, Reeves P, Deeming S, et al. Encouraging translation and assessing impact of the Centre for Research Excellence in Integrated Quality Improvement: rationale and protocol for a research impact assessment. *BMJ Open* 2017;7(12).				1			1
Bailie R, Bailie J, Larkins S, Broughton E. Editorial: Continuous quality improvement (CQI) – advancing understanding of design, application, impact, and evaluation of CQI approaches. *Front Public Health* 2017;5(306).				1			1
Bailie R, Larkins S, Broughton E. Continuous Quality Improvement – Advancing Understanding of Design, Application, Impact and Evaluation of CQI Approaches. Lausanne, Switzerland: Frontiers Media SA 2017.				1	1		

McAullay D, McAuley K, Bailie R, et al. Sustained participation in annual continuous quality improvement activities improves quality of care for Aboriginal and Torres Strait Islander children. *J Paediatr Child Health* 2018;54(2):132–40.				1	1		
Edmond KM, McAuley K, McAullay D, et al. Quality of social and emotional wellbeing services for families of young Indigenous children attending primary care centers; a cross sectional analysis. *BMC Health Serv Res* 2018;18(1).				1	1		
Gibson-Helm ME, Bailie J, Matthews V, et al. Identifying evidence-practice gaps and strategies for improvement in Aboriginal and Torres Strait Islander maternal health care. *PLoS ONE* 2018;13(2):e0192262.				1	1		
Bailie J, Matthews V, Laycock A, et al. Rigorous follow-up systems for abnormal results are essential to improve health outcomes for Aboriginal and Torres Strait Islander people. *Aust J Prim Health* 2018;24:1–3.				1			1
McCalman J, Bailie R, Bainbridge R, et al. Continuous quality improvement and comprehensive primary health care: a systems framework to improve service quality and health outcomes. *Front Public Health* 2018;6.				1			1
McPhail-Bell K, Matthews V, Bainbridge R, et al. An 'All Teach, All Learn' approach to research capacity strengthening in Indigenous primary health care continuous quality improvement. *Front Public Health* 2018;6.				1		1	
McCalman J, Bainbridge R, Brown C, et al. The Aboriginal Australian Family Wellbeing Program: a historical analysis of the conditions that enabled its spread. *Front Public Health* 2018;6.				1			1
Bailie J, Cunningham FC, Bainbridge RG, et al. Comparing and contrasting 'innovation platforms' with other forms of professional networks for strengthening primary healthcare systems for Indigenous Australians. *BMJ Glob Health* 2018;3(3).				1	1		
Meiklejohn JA, Arley B, Bailie R, et al. Community-identified recommendations to enhance cancer survivorship for Aboriginal and Torres Strait Islander people. *Aust J Prim Health* 2018;24(3):233–40.				1	1		
Bailie J, Boyle JA, Bailie RS. Population attributable fractions of perinatal outcomes for nulliparous women associated with overweight and obesity, 1990–2014. *Med J Aust* 2018;208(11):505–6.				1			1
Cunningham FC, Matthews V, Sheahan A, et al. Assessing collaboration in a National Research Partnership in Quality Improvement in Indigenous Primary Health Care: a network approach. *Front Public Health*. 2018;6(182).				1		1	
Onnis L-A, Klieve H, Tsey K. The evidence needed to demonstrate impact: A synthesis of the evidence from a phased social and emotional wellbeing intervention. *Eval Program Plann* 2018;70:35–43.				1	1		

Ralph AP, de Dassel JL, Kirby A, et al. Improving delivery of secondary prophylaxis for Rheumatic Heart Disease in a high-burden setting: outcome of a stepped-wedge, community, randomized trial. *J Am Heart Assoc: Cardiovascular and Cerebrovascular Disease* 2018;7(14).				1		1	
Heyeres M, Kinchin I, Whatley E, et al. Evaluation of a residential mental health recovery service in North Queensland. *Front Public Health* 2018;6:123.				1	1		
Read C, Mitchell AG, de Dassel JL, et al. Qualitative evaluation of a complex intervention to improve Rheumatic Heart Disease secondary prophylaxis. *J Am Heart Assoc*. 2018;7(14).				1	1		
Nattabi B, Girgis S, Matthews V, et al. Clinic predictors of better syphilis testing in Aboriginal primary healthcare: a promising opportunity for primary healthcare service managers. *Aust J Prim Health* 2018;24(4):350–8.				1	1		
Edmond KM, Tung S, McAuley K, et al. Improving developmental care in primary practice for disadvantaged children. *Arch Dis Childhood* 2019;104(4):372–80.				1	1		
Strobel NA, McAuley K, Matthews V, et al. Understanding the structure and processes of primary health care for young indigenous children. *J Prim Health Care* 2018;10(3):267–78.				1		1	
Onnis L-A, Hakendorf M, Tsey K. How are Continuous Quality Improvement (CQI) approaches used in evaluating management development programs? a literature review. *Asia Pacific Journal of Health Management* 2018;13(2):1–15.				1			1
Smith G, Kirkham R, Gunabarra C, et al. 'We can work together, talk together': an Aboriginal health care home. *Aust Health Rev* 2018;43:486–91.				1		1	
Tsey K, Lui SM, Heyeres M, et al. Developing soft skills: exploring the feasibility of an Australian well-being program for health managers and leaders in Timor-Leste. *SAGE Open* 2018;8(4).				1			1
Laycock A, Harvey G, Percival N, et al. Application of the i-PARIHS framework for enhancing understanding of interactive dissemination to achieve wide-scale improvement in Indigenous primary healthcare. *Health Res Policy Syst* 2018;16(1).				1	1		
de Witt A, Cunningham FC, Bailie R, et al. 'It's just presence', the contributions of Aboriginal and Torres Strait Islander health professionals in cancer care in Queensland. *Front Public Health* 2018;6:344.				1		1	
Zuchowski I, Miles D, Gair S, et al. K. Social work research with industry: a systematic literature review of engagement and impact. *Br J Soc Work* 2019;49(8):2299–324.				1			1
Heyeres M, Tsey K, Yang Y, et al. The characteristics and reporting quality of research impact case studies: a systematic review. *Eval Program Plann* 2019;73:10–23.				1			1

Laycock AF, Bailie J, Percival NA, et al. Wide-scale continuous quality improvement: a study of stakeholders' use of quality of care reports at various system levels, and factors mediating use. *Front Public Health* 2019;6.				1	1		
Bailie J, Laycock A, Matthews V, et al. Emerging evidence of the value of health assessments for Aboriginal and Torres Strait Islander people in the primary healthcare setting. *Aust J Prim Health* 2019;25(1):1–5.				1			1
Tsey K, Onnis L-A, Whiteside M, et al. Assessing research impact: Australian Research Council criteria and the case of Family Wellbeing research. *Eval Program Plann* 2019;73:176–86.				1	1		
Lestari T, Graham S, Van den Boogard C, et al. Bridging the knowledge-practice gap in tuberculosis contact management in a high-burden setting: a mixed-methods protocol for a multicenter health system strengthening study. *Implement Sci* 2019;14(1):31.				1		1	
Onnis L-A, Hakendorf M, Diamond M, et al. CQI approaches for evaluating management development programs: a case study with health service managers from geographically remote settings. *Eval Program Plann* 2019;74:91–101.				1			1
Turner NN, Taylor J, Larkins S, et al. Conceptualizing the association between community participation and CQI in Aboriginal and Torres Strait Islander PHC services. *Qual Health Res* 2019;29(13):1904–15.				1	1		
Gunaratnam P, Schierhout G, Brands J, et al. Qualitative perspectives on the sustainability of sexual health continuous quality improvement in clinics serving remote Aboriginal communities in Australia. *BMJ Open* 2019;9(5):e026679.				1	1		
Valery PC, Bernardes CM, De Witt A, et al. Patterns of primary health care service use of Indigenous Australians diagnosed with cancer. *Support Care Cancer* 2020;28(1):317–27.				1	1		
Mitchinson C, Strobel N, McAullay D, et al. Anemia in disadvantaged children aged under five years: quality of care in primary practice. *BMC Pediatr* 2019;19(1):178.				1			1
Larkins S, Carlisle K, Turner N, et al. 'At the grass roots level it's about sitting down and talking': exploring quality improvement through case studies with high-improving Aboriginal and Torres Strait Islander primary healthcare services. *BMJ Open* 2019;9(5):e027568.				1		1	
Conte KP, Gwynn J, Turner N, Koller C, Gillham KE. Making space for Aboriginal and Torres Strait Islander community health workers in health promotion. *Health Promot Int* 2019.				1	1		
Carroll SJ, Dale MJ, Bailie R, et al. Climatic and community sociodemographic factors associated with remote Indigenous Australian smoking rates: an ecological study of health audit data. *BMJ Open* 2019;9(7).				1			1

Preston R, Rannard S, Felton-Busch C, et al. How and why do participatory women's groups (PWGs) improve the quality of maternal and child health (MCH) care? A systematic review protocol. *BMJ Open* 2019;9(9):e030461.				1			1
Laycock A, Bailie J, Matthews V, et al. Using developmental evaluation to support knowledge translation: reflections from a large-scale quality improvement project in Indigenous primary healthcare. *Health Res Policy Syst* 2019;17(1):70.				1	1		
Diaz A, Vo B, Baade PD, Matthews V, et al. Service level factors associated with cervical screening in Aboriginal and Torres Strait Islander primary health care centres in Australia. *Int J Environ Res Public Health* 2019;16(19):3630.				1	1		
Kinchin I, Russell AM, Tsey K, et al. Psychiatric inpatient cost of care before and after admission at a residential subacute step-up/step-down mental health facility. *J Med Econ* 2019;22(5):491–8.				1		1	
Lopez-Carmen V, McCalman J, Benveniste T, Askew D, Spurling G, Langham E, et al. Working together to improve the mental health of indigenous children: a systematic review. *Child Youth Serv Rev* 2019;104:104408.				1			1
Tsey K. Working on Wicked Problems: A Strengths-based Approach to Research Engagement and Impact. Basel, Switzerland: Springer Nature 2019.				1			1
Cunningham FC, Ranmuthugala G, Westbrook JI, et al. Tackling the wicked problem of health networks: the design of an evaluation framework. *BMJ Open* 2019;9(5):e024231.				1		1	
Onnis L-A, Moylan R, Whiteside M, et al. Integrating the Family Wellbeing Program into practice: a conceptual model. *Australian Social Work* 2019:1–14.				1	1		
Carrington A, Dewar S, Kinchin I, et al. A police-led community response to child abuse and youth sexual violence and abuse in Indigenous communities in Far North Queensland: 'Speak up. Be strong. Be heard'. *Child Abuse Negl* 2019;98:104228.				1			1
Fazelipour M, Cunningham F. Barriers and facilitators to the implementation of brief interventions targeting smoking, nutrition, and physical activity for indigenous populations: a narrative review. *Int J Equity Health* 2019;18(1):169.				1	1		
Katzenellenbogen J, Bond-Smith D, Ralph A, et al. Priorities for improvement in management of Acute Rheumatic Fever and Rheumatic Heart Disease: analysis of cross-sectional continuous quality improvement data in Aboriginal primary health care centres in Australia. *Aust Health Rev* 2019.				1	1		
Quinn E, Girgis S, Van Buskirk J, Matthews V, Ward JE. Clinic factors associated with better delivery of secondary prophylaxis in acute rheumatic fever management. *Aust J Gen Pract* 2019;48(12):859.				1	1		

Adily A, Girgis S, D'Este C, Matthews V, Ward JE. Syphilis testing performance in Aboriginal primary health care: exploring impact of continuous quality improvement over time. *Aust J Prim Health* 2020.				1	1		

The RECORD statement – checklist of items, extended from the STROBE statement, that should be reported in observational studies using routinely collected health data.

	Item No.	STROBE items	Location in manuscript where items are reported	RECORD items	Location in manuscript where items are reported
Title and abstract					
	1	(a) Indicate the study's design with a commonly used term in the title or the abstract (b) Provide in the abstract an informative and balanced summary of what was done and what was found	Title and abstract	RECORD 1.1: The type of data used should be specified in the title or abstract. When possible, the name of the databases used should be included. RECORD 1.2: If applicable, the geographic region and timeframe within which the study took place should be reported in the title or abstract. RECORD 1.3: If linkage between databases was conducted for the study, this should be clearly stated in the title or abstract.	Title and abstract Abstract, though some information in title also. NA
Introduction					
Background rationale	2	Explain the scientific background and rationale for the investigation being reported	Introduction paragraphs 1 -3		
Objectives	3	State specific objectives, including any prespecified hypotheses	Introduction paragraph 3		
Study Design	4	Present key elements of study design early in the paper	Title, Abstract, Introduction and Methods		
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	Setting described, specifically see Table 1; along with time periods (2002-		

			2004; 2005-2009; 2010-2014; 2015-2019)		
Participants	6	*(a) Cohort study* - Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study* - Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study* - Give the eligibility criteria, and the sources and methods of selection of participants *(b) Cohort study* - For matched studies, give matching criteria and number of exposed and unexposed *Case-control study* - For matched studies, give matching criteria and the number of controls per case	Persons and the organisations they were affiliated with were included if they co-authored a relevant publication in the study period as described in methods.	RECORD 6.1: The methods of study population selection (such as codes or algorithms used to identify subjects) should be listed in detail. If this is not possible, an explanation should be provided. RECORD 6.2: Any validation studies of the codes or algorithms used to select the population should be referenced. If validation was conducted for this study and not published elsewhere, detailed methods and results should be provided. RECORD 6.3: If the study involved linkage of databases, consider use of a flow diagram or other graphical display to demonstrate the data linkage process, including the number of individuals with linked data at each stage.	Persons and the organisations they were affiliated with were included if they co-authored a relevant publication in the study period as described in methods. NA NA
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable.	Definitions of categories provided in manuscript. In Methods section under heading 'Data categorisation, standardisation and cleaning'	RECORD 7.1: A complete list of codes and algorithms used to classify exposures, outcomes, confounders, and effect modifiers should be provided. If these cannot be reported, an explanation should be provided.	Definitions of categories provided in manuscript. In Methods section under heading 'Data categorisation, standardisation and cleaning'

Data sources/ measurement	8	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	Detailed in results - Table 3		Detailed in results – Table 3.
Bias	9	Describe any efforts to address potential sources of bias	Detailed in methods, eg. Having two authors undertaking categorisation in a blind manner, then conferring for any discrepancies; group analysis processes by reviews of co-authors.		Detailed in methods, eg. Having two authors undertaking categorisation in a blind manner, then conferring for any discrepancies; group analysis processes by reviews of co-authors.
Study size	10	Explain how the study size was arrived at	Detailed in methods – eg Publications within the period under study.		Detailed in methods eg. Publications within the period under study.
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen, and why	NA		
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding (b) Describe any methods used to examine subgroups and interactions	NA		

		(c) Explain how missing data were addressed (d) *Cohort study* - If applicable, explain how loss to follow-up was addressed *Case-control study* - If applicable, explain how matching of cases and controls was addressed *Cross-sectional study* - If applicable, describe analytical methods taking account of sampling strategy (e) Describe any sensitivity analyses			
Data access and cleaning methods		..		RECORD 12.1: Authors should describe the extent to which the investigators had access to the database population used to create the study population. RECORD 12.2: Authors should provide information on the data cleaning methods used in the study.	Noted in Methods eg. Internal project records used. Publications retrieved from publicly available sources.
Linkage		..		RECORD 12.3: State whether the study included person-level, institutional-level, or other data linkage across two or more databases. The methods of linkage and methods of linkage quality evaluation should be provided.	NA
Results					
Participants	13	(a) Report the numbers of individuals at each stage of the study (*e.g.*, numbers potentially eligible, examined for eligibility, confirmed eligible, included in		RECORD 13.1: Describe in detail the selection of the persons included in the study (*i.e.,* study population selection) including filtering based on data quality, data availability and linkage. The selection of included persons can	Noted in methods – eg. Persons and the organisations they were affiliated with were included if

		the study, completing follow-up, and analysed) (b) Give reasons for non-participation at each stage. (c) Consider use of a flow diagram		be described in the text and/or by means of the study flow diagram.	they co-authored a relevant publication in the study period as described in methods.
Descriptive data	14	(a) Give characteristics of study participants (*e.g.*, demographic, clinical, social) and information on exposures and potential confounders (b) Indicate the number of participants with missing data for each variable of interest (c) *Cohort study* - summarise follow-up time (*e.g.*, average and total amount)	Table 3 in the results contains characteristics of study participants.		
Outcome data	15	*Cohort study* - Report numbers of outcome events or summary measures over time *Case-control study* - Report numbers in each exposure category, or summary measures of exposure *Cross-sectional study* - Report numbers of outcome events or summary measures	NA		
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (e.g., 95% confidence interval). Make clear which confounders were adjusted for and why they were included (b) Report category boundaries when continuous variables were categorized	In results in Table 3 eg. (b) Phases of the network (time) were based on funding cycles.		

		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period			
Other analyses	17	Report other analyses done—e.g., analyses of subgroups and interactions, and sensitivity analyses	Table 3 in results eg. Descriptive counts and percentages. Network measures as described in methods section.		
Discussion					
Key results	18	Summarise key results with reference to study objectives	Paragraph 1 of Discussion		
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	Discussion – under heading 'strengths and limitations'	RECORD 19.1: Discuss the implications of using data that were not created or collected to answer the specific research question(s). Include discussion of misclassification bias, unmeasured confounding, missing data, and changing eligibility over time, as they pertain to the study being reported.	NA
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	Discussion - The results of the study are compared to findings from other national and international studies.		
Generalisability	21	Discuss the generalisability (external validity) of the study results	Discussion - The lack of generalisability to other settings is noted		
Other Information					
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable,	Funding source provided to the BMJ Quality and Safety		

		for the original study on which the present article is based	Journal, though it is not in the article (at this stage) for the Journal has a triple blind review process.		
Accessibility of protocol, raw data, and programming code		..		RECORD 22.1: Authors should provide information on how to access any supplemental information such as the study protocol, raw data, or programming code.	Noted in the BMJ Quality and Safety submission process that the data is available on reasonable request to the corresponding author, and it adheres to the ethics approval.

*Reference: Benchimol EI, Smeeth L, Guttmann A, Harron K, Moher D, Petersen I, Sørensen HT, von Elm E, Langan SM, the RECORD Working Committee. The REporting of studies Conducted using Observational Routinely-collected health Data (RECORD) Statement. *PLoS Medicine* 2015; in press.