BMJ Global Health

Damage to medical complexes in the Gaza Strip during the Israel–Hamas war: a geospatial analysis

Danielle N Poole ,[1,2] Daniel Andersen,[1] Nathaniel A Raymond,[1] Rob Grace,[3] Trevor Smith,[4] Kaveh Khoshnood,[1] Hani Mowafi[5]

To cite: Poole DN, Andersen D, Raymond NA, *et al*. Damage to medical complexes in the Gaza Strip during the Israel–Hamas war: a geospatial analysis. *BMJ Glob Health* 2024;**9**:e014768. doi:10.1136/bmjgh-2023-014768

Handling editor Seye Abimbola

Received 7 December 2023
Accepted 28 December 2023

[1]Epidemiology of Microbial Diseases Department, Yale University School of Public Health, New Haven, Connecticut, USA
[2]University of Heidelberg, Heidelberg, Germany
[3]Department of Political Science, Boston University, Boston, Massachusetts, USA
[4]Yale University Divinity School, New Haven, Connecticut, USA
[5]Yale University School of Medicine, New Haven, Connecticut, USA

Correspondence to
Dr Danielle N Poole;
danielle.poole@yale.edu

ABSTRACT

Introduction Medical facilities are civilian objects specially protected during armed conflict by international humanitarian law (IHL). These protections are customarily applied regardless of the conflict, parties or contexts involved. Attacks on medical care have characterised the bombardment campaign of the Gaza Strip beginning 7 October 2023. This study presents evidence regarding patterns of damage to medical complexes relative to all other buildings in the first month of this conflict.

Methods This is an observational pre/post-study of damage to buildings during the first month of the Israel Defence Force bombardment of Gaza from 7 October to 7 November 2023. Open-source polygons for the Gaza Strip were spatially joined with building damage assessments from satellite imagery analysis. Medical facilities were included in the analysis if they were cross-referenced by a minimum of two datasets. Logistic regression was used to test for statistically significant differences in the proportions of damaged medical complexes and other buildings.

Results A total of 167 292 unique buildings were identified, including 106 cross-referenced medical complexes. Approximately 9% of non-medical buildings and medical complexes alike sustained damage during the first month of the bombardment. No difference in the odds of damage was detected between medical complexes and all other buildings (OR: 0.89; 95% CI: 0.45-1.76; p>0.74).

Conclusion There is a lack of evidence of differential damage to medical and non-medical complexes during the first month of the bombing campaign. This finding raises concerns about combatants' application of the principles of distinction, proportionality and precaution, suggesting the importance of further investigation.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Previous studies have demonstrated the importance of documenting attacks on medical facilities during ongoing conflict for accountability. Reports of attacks on medical care in Gaza during the current escalation of the conflict are widespread, but have not yet identified the comprehensive and comparative pattern of damage sustained by medical complexes relative to other buildings.

WHAT THIS STUDY ADDS

⇒ This geospatial analysis of infrastructure damage sustained in the Gaza Strip from 7 October to 7 November 2023 assessed the proportions of damage to medical complexes and other buildings during the bombardment campaign. The proportion of damage to medical complexes was similar to all other buildings despite their status as protected civilian objects by international humanitarian law. This is the first empirical investigation of the pattern of damage to medical care in the ongoing Israel–Hamas conflict.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This analysis raises concerns about combatants' application of the principles of distinction, proportionality and precaution, suggesting the importance of further investigation. Future research may include investigations of damage to medical complexes, as well as other protected civilian infrastructure, over time as new patterns may emerge during this ongoing conflict.

INTRODUCTION

International humanitarian law (IHL) includes three principles of engagement in armed conflict: distinction, proportionality and precaution with respect to civilian objects—which are all buildings and infrastructure not regarded as a military objective, including schools, domiciles, transportation and medical units. The term 'medical units' refers to 'establishments and other units, whether military or civilian, organised for medical purposes, be they fixed or mobile, permanent or temporary, including, for example, hospitals and other similar units, blood transfusion centres, preventive medicine centres and institutes, medical depots and the medical and pharmaceutical stores of such units'.[1] IHL grants medical establishments, including hospitals, special protected status.[2–6] Whether indiscriminate or intentional, attacks on protected medical units are

incongruent with the principles of IHL and constitute violations of the law under the Geneva Conventions and their Additional Protocols.

Under IHL, operating medical facilities may under no circumstance be the object of attacks unless they are used, outside of their humanitarian function, to 'commit acts that are harmful to the enemy'. If a protected medical facility dually represents a military object, the principle of *proportionality* prohibits attacks against military objects that are expected to cause incidental harm to civilians or civilian objects that would be excessive in relation to the anticipated military benefit. Furthermore, the principle of *precaution* requires that parties to armed conflict take all feasible measures to avoid or minimise civilian harm and damage to civilian objects. Consequently, all parties to an armed conflict have an obligation to *distinguish* between infrastructure with protected status (eg, medical complexes) and other infrastructure that may have primary military use, and to minimise the civilian impact of all military activities.

Despite protection conferred by IHL, armed conflicts around the world have been characterised by attacks on medical care. The WHO defines an attack on medical care as any act of verbal or physical violence or obstruction or threat of violence that interferes with the availability, access, and delivery of curative and/or preventative services during an emergency. The ongoing Israel–Hamas war has been marked by attacks on medical care: the WHO documented a total of 33 attacks on healthcare carried out in Israel during attacks by Hamas and other militants on 7 October 2023, followed by 335 attacks on medical care in the occupied Palestinian territory (oPt).[7] Documenting attacks against medical care during armed conflict can reveal the types and patterns of violations against patients, personnel or facilities.[8]

Satellite imagery damage classification is often the only tool available for empirically detecting and further investigating the effects of conflict on medical complexes during ongoing armed conflict.[9 10] Such remote assessment is increasingly central to the collection of evidence of alleged war crimes and human rights violations,[11 12] including as evidence in cases before the International Criminal Tribunals for the former Yugoslavia, the International Criminal Court and the International Court of Justice.[13–15]

Today, near real-time, georeferenced damage classification can be performed in non-permissive conflict environments using publicly available satellite imagery[16] and analysis products. Investigating the geospatial pattern of attacks on medical complexes may provide empirical evidence of widespread attacks on medical care, raising concern for a lack of protection, proportionality and precaution.

To test whether the proportions of damage were the same for medical complexes and non-medical buildings, we leveraged a publicly available satellite imagery building damage assessment dataset and medical infrastructure databases to examine the extent of damage to non-medical buildings and medical complexes in the Gaza Strip during the first month of the Israel Defense Forces (IDF) bombardment campaign.

METHODS

This study compares damage to medical complexes relative to all buildings within the Gaza Strip, oPt during the first month of the IDF bombardment campaign from 7 October to 7 November 2023.

Study setting

The Gaza Strip covers an area of 360 km^2 and includes the governorates of Deir al-Balah, Gaza, Khan Yunis, North Gaza and Rafah. The population of the Gaza Strip prior to the escalation was 2.1 million inhabitants, including 1.7 million Palestine refugees.[17]

Study design

This observational, pre/post-quasi-experimental study identifies the effects of the IDF bombardment campaign on medical complexes, which are protected civilian infrastructure, within the Gaza Strip.

Data sources

Publicly available, georeferenced building footprints, damage assessments and medical designations were spatially joined to generate an empirical census of infrastructure damage within the Gaza Strip.

Administrative boundaries

Shapefiles storing the attribute information of geographical features, including subnational administrative boundaries for the State of Palestine, including the oPt, were obtained from the United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) available at: https://data.humdata.org/dataset/cod-ab-pse.

Georeferenced building footprint data

Polygons for all buildings within the Gaza Strip were obtained from OpenStreetMap (OSM),[18] a collaborative project designed to create a free and editable geospatial database.

Georeferenced medical complex data

Four open sources were used to generate a cross-referenced dataset of medical complex locations.

First, point data for all medical facilities in a UNOCHA dataset prepared by the Palestinian National Institute of Public Health and United Nations Relief and Work Agency for Palestinian Refugees in the Near East were extracted (n=101).[19] This dataset was last updated in December 2021.

Second, medical facility locations identified in the Gaza Strip by the WHO Health Cluster (n=79)[20] were manually georeferenced in ArcGIS.[21]

Third, the geocoordinates of all points and polygons labelled as 'medical' with subcategorisation as 'hospital', 'clinic' or 'doctor' within the OSM dataset were extracted (n=144 and n=110, respectively).[18]

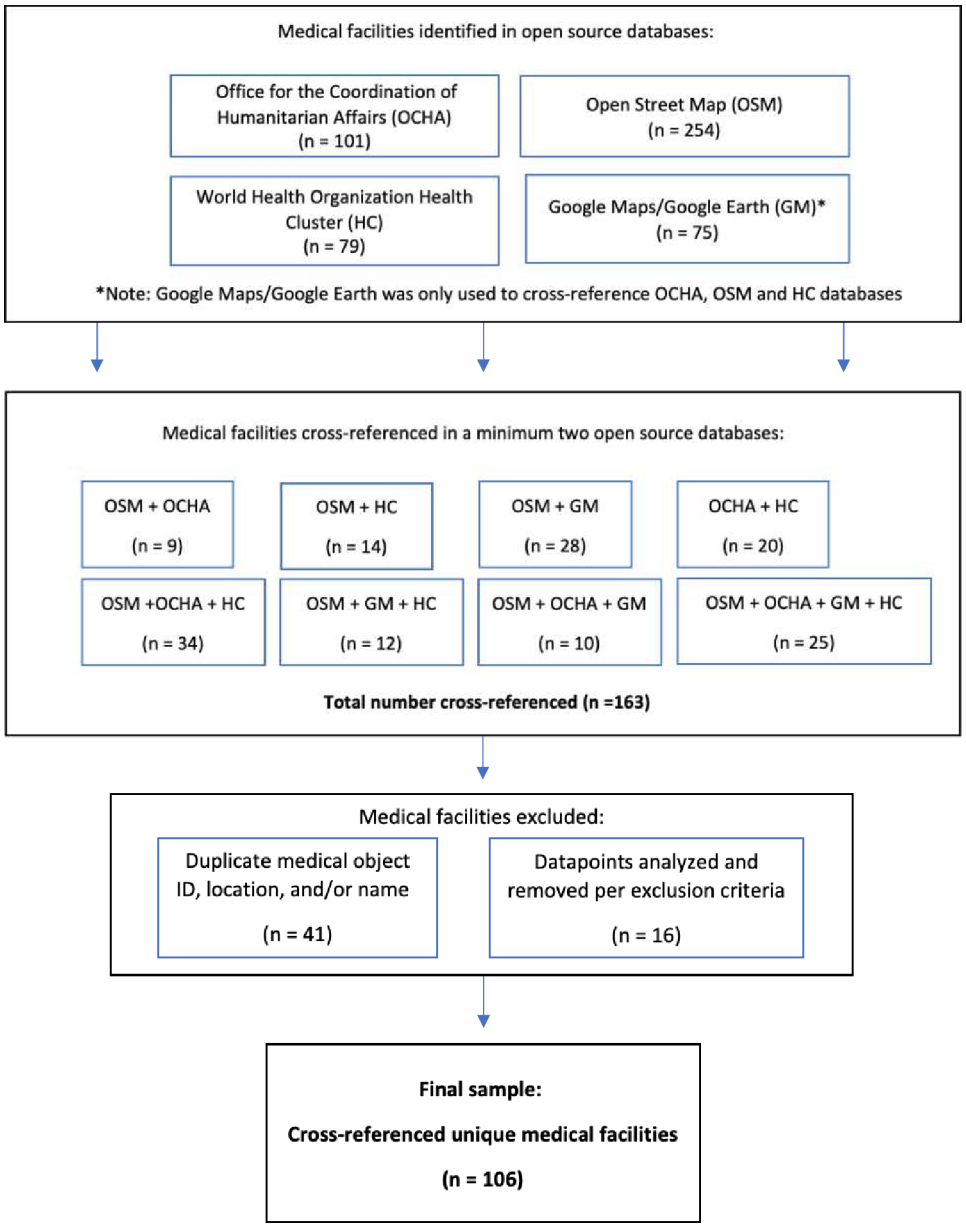

Figure 1 Medical complex inclusion.

Finally, all buildings labelled 'medical' by Google Maps in the Gaza Strip were extracted (n=75). Medical points from these four sources (OSM, UNOCHA, WHO Health Cluster and Google Maps) were cross-referenced in a minimum of two datasets as described in figure 1. In cases of location (including misalignment of point coordinates with a polygon) and/or facility name discrepancies between two open-source databases, the OCHA dataset, or the majority consensus among three or more databases, was used as the reference. Duplicate facilities and private clinics, dental offices, diagnostic centres (eg, laboratories and radiology centres) and pharmacies were removed from the final dataset. Despite being protected infrastructure under IHL, they are frequently located in general or multi-use buildings. Facilities in multi-use buildings were excluded from this analysis. We limited included facilities to those that were deemed clearly discernible, distinct medical complexes.

For larger hospital complexes identified in the OSM medical polygon list with multiple OSM building polygons, OSM polygons were combined to create a single hospital complex. United Nations Satellite Centre (UNOSAT)-identified points of damage were then referenced to OSM polygons to get a list of all damaged OSM building polygons. All cross-referenced medical complexes were spatially joined to the OSM polygon layer of building footprints.

Damage classification

Satellite imagery-based building damage assessments for the Gaza Strip, oPt were obtained from UNOSAT. Since 2003, UNOSAT has provided satellite image analysis

Table 1 Damage classification scale

Damage scale	Definition
Grade 1: possible damage	Assessed building does not appear to be damaged but debris is visible around the building structure.
Grade 2: moderate damage	Limited damage observed to the building structure on many occasions adjacent to destroyed or heavily damaged buildings.
Grade 3: severe damage	Part of the building structure collapsed, such as part of the roof or one or more fallen walls.
Grade 4: destroyed	All or most of the building structure has collapsed.

Adapted from United Nations Satellite Centre.

during humanitarian emergencies related to disasters, complex emergencies and conflict situations.

Details of the UNOSAT damage classification methodology have been previously described.[22] Briefly, damage detected on a satellite image from 7 November 2023 was compared with structural assessments from satellite images collected on 1 May 2023, 10 May 2023, 18 September 2023 and 15 October 2023 to comprehensively determine the structural integrity of buildings prior to the start of the present bombardment campaign. The damage classification scale is presented in table 1.

A minimum of two UNOSAT analysts manually completed each damage assessment on separate areas of the Gaza Strip, analysing all buildings in the process. A quality control check was performed by a senior analyst to reconcile their results and ensure accuracy.

Patient and public involvement

This study includes data generated for decision-making by UNOSAT as well as publicly produced geolocated medical complex data. The findings of this study will be disseminated to the public via popular media.

Geospatial analysis

The damage assessment point data were spatially joined to the building footprints within the Gaza Strip. Polygons labelled as a 'greenhouse' or 'greenhouse_horticulture' (n=5931) were excluded because these building types were not included in the UNOSAT building damage assessment dataset. Damage to all buildings and medical complexes was visualised by spatially joining the damage point data to the medical complex and other building polygon layers in ArcGIS V.10.8.1.[21]

Statistical analysis

Attribute data from the final map containing the damage points, building footprints and medical complex locations were used to quantify the pattern of damage to buildings in the Gaza Strip. The proportions of damaged medical and non-medical buildings are calculated directly from the observed, complete census dataset. Logistic regression was conducted to test whether there was a statistically significant difference in the proportion of damage and damage severity between medical complexes and non-medical buildings. Additionally, we estimated the number of damaged medical complexes that would have resulted in a statistically significantly lower proportion of damage relative to the observed proportion of damage to non-medical buildings by iteratively running the logistic regression model until the null hypothesis of no difference was reached. Sensitivity analyses accounting for unknown variance and unequal sample size are presented in the online supplemental appendix 1.

A significance level of 0.05 was used. All statistical analyses were conducted in Stata V.17.0.[23]

RESULTS

A total of 167 292 buildings in the Gaza Strip were assessed for damage during the study period, from 7 October to 7 November 2023. Of these buildings, 106 represent cross-referenced medical complexes. Overall, 9% of non-medical buildings (n=15 768) and medical complexes (n=9) were damaged during the first month of the IDF bombardment campaign.We did not detect a statistically significant difference between the proportion of damage to medical complexes and all other buildings (OR: 0.89; 95% CI: 0.45-1.76; p>0.74). Furthermore, six fewer medical complexes would need to be classified as "not damaged" to produce a significant difference in the odds of damage consistent with protection. The geospatial distribution of damage is presented in figure 2.

The severity of damage to buildings in the Gaza Strip is presented in table 2.

Medical complexes had a higher percentage of severe damage and destruction (55%) relative to non-medical buildings (45%), although the odds of damage were not statistically significant (p>0.54) (table 2).

DISCUSSION

Medical complexes sustained damage similar to non-medical buildings during the first month of the IDF bombardment campaign on the Gaza Strip. This conclusion is supported both by the observed proportions of damage, which are the same for medical complexes and all other buildings, and the logistic regression model, which did not identify a statistically significant difference in the odds of damage. Further infrastructure damage has been widely reported with subsequent analyses of UNOSAT data through 26 November estimating that 18% of all structures in Gaza[24] and up to 50% of buildings in Northern Gaza were damaged.[25] Such extensive damage to Gaza's health and civil infrastructure will have immediate and long-term health impacts by limiting the ability to respond to the current crisis and severely decreasing the ability to provide for the ongoing medical needs of the population after the war ends.[26–29]

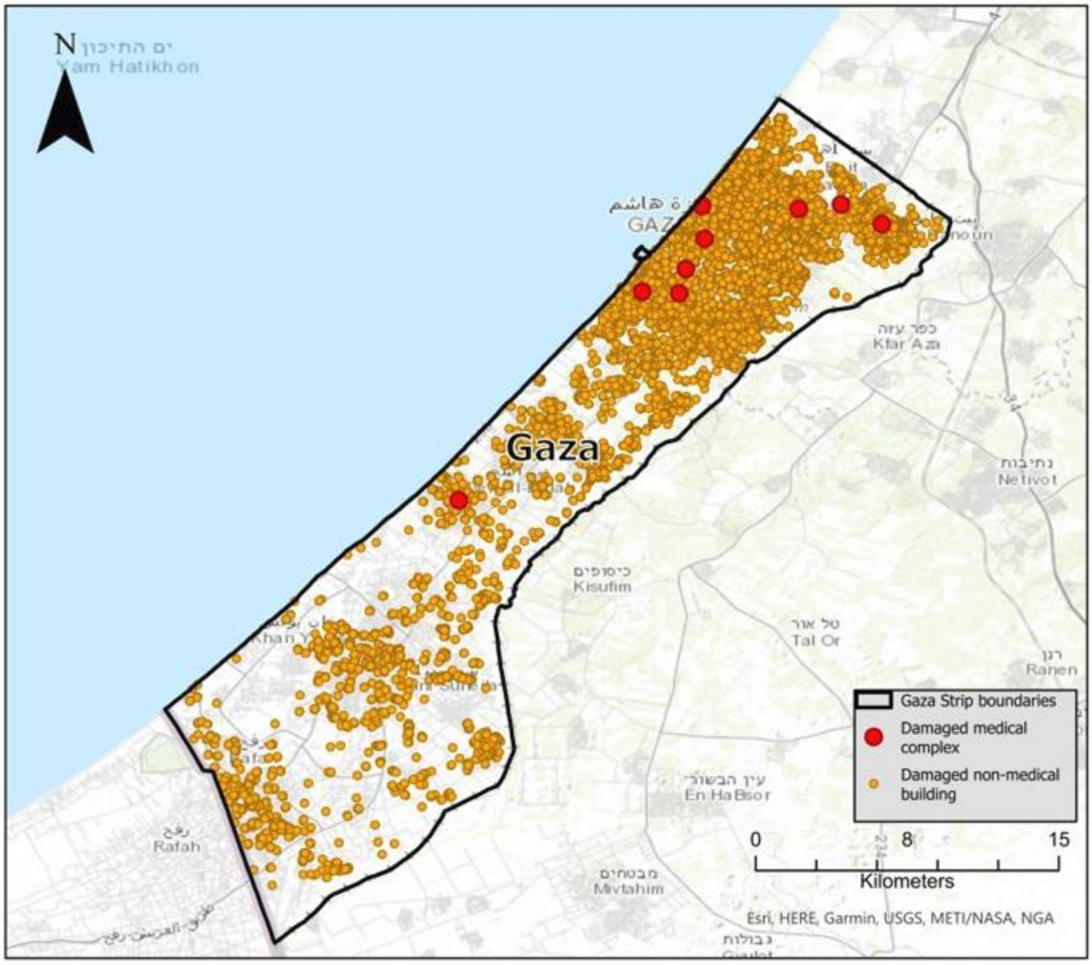

Figure 2 Damage to medical complexes and all other buildings in the Gaza Strip, 7 October–7 November 2023.

From 7 October to 7 November 2023, the WHO Surveillance System for Attacks on Health Care reports 140 attacks impacting health facilities in oPt and 15 attacks impacting health facilities in Israel during the study time period. By 22 January 2024, the numbers of these types of attacks rose to 325 and 18 in oPt and Israel, respectively.[30 28 29] Beyond damage to protected medical infrastructure, damage to other protected civilian objects in Gaza and Israel - such as housing, schools, and public health infrastructure - not included in this assessment, raise further concerns about civilian harm in this conflict.

A reoccurring challenge to the application of IHL is that in order to designate a medical complex as a legitimate target, the attacker must confirm that the facility has ceased to serve a purely humanitarian function and that it is being used for military operations.[31] Even if a medical facility is occupied or used by combatants, IHL stipulates that an attacker must consider the proportionality of the attack with respect to the expected incidental harm to civilians or civilian objects that would be excessive in relation to the anticipated military benefit; and take all feasible measures to avoid or minimise such harms. Geospatial analysis alone cannot speak to the intent of combatants, nor can it assess the use of medical complexes for military purposes. Moreover, the data presented in this study can not attribute damage to a particular combatant. Nonetheless, geospatial patterns of widespread damage to medical complexes at rates comparable to other infrastructure raise concerns that in this conflict medical facilities have not received the respect

Table 2 Damage to medical complexes and non-medical facilities

	Damage classification			
Facility type	**Destroyed N (%)**	**Severe damage N (%)**	**Moderate damage N (%)**	**Total**
Medical complex	2 (22)	3 (33)	4 (44)	9
Non-medical	3122 (20)	4025 (26)	8621 (55)	15768
Total	3124	4028	8625	15777

and protections customarily afforded by the framework of IHL.

Limitations

This study has several limitations. The interpretation of geospatial findings to support accountability for alleged war crimes should follow statistical reasoning and be considered in the context of data limitations and a preponderance of evidence from multiple sources. First, high technical standards for verifying damage to medical complexes may result in the under-reporting of events, leading to overly conservative results. Second, damage assessments conducted primarily using satellite imagery are limited to features visible to analysts and may not always detect damage to a structure's sides and interior. Third, damage assessments may be subject to bias, including misclassification bias. Validating damage assessments represents an important next step in the field of humanitarian remote sensing. However, any misclassification bias in the present dataset is expected to be the same for medical and non-medical infrastructure, as no distinction was made between building use during the damage assessment process. Fourth, the sample of damaged medical complexes is relatively small; however, issues associated with low events per variable (EPV) are highly uncommon with an EPV of nine.[32] Finally, a narrow definition of medical complex was used in this study. Only free-standing medical complexes were evaluated as damage assessments were conducted at the building level. Thus, other protected medical units, such as pharmacies, dental offices and clinics in multi-use buildings, were excluded. We were unable to cross-reference all medical complexes identified by UNOCHA and the United Nations Health Cluster and thus additional facilities were excluded that may have been active medical units. Together, these methodological factors produce a conservative estimate of damage.

CONCLUSION

In the first weeks of the Israel–Hamas conflict, medical complexes sustained similar patterns of damage relative to other buildings. That is, during the first month of the bombing campaign, the proportion of damage to medical complexes was similar to all other buildings despite their status as protected civilian objects by IHL. This finding raises concerns about the combatants' application of the principles of distinction, proportionality and precaution with respect to medical units. This evidence supports calls for more protection of medical care[33 34] and civilians.[35 36] Finally, this study highlights the need for further investigation of damage, including to other protected civilian infrastructure as well as medical complexes, as patterns of this ongoing conflict may evolve over time.

X Danielle N Poole @drdaninpoole

Acknowledgements This manuscript includes critical scholarly contributions of anonymous authors of the Yale Humanitarian Research Lab. The authors are grateful for the UNOSAT analysts who conducted the comprehensive damage assessment of the Gaza Strip.

Contributors DNP conceptualised, supervised, and developed the study methodology and analysis, cowrote the original draft, and serves as the guarantor. DA curated, visualised and interpreted the data, managed the project, and developed the study methodology and analysis. NAR conceptualised and developed the study methodology. RG interpreted the data and cowrote the original draft. TS curated and interpreted the data. KK conceptualised the study. AHRL curated and interpreted the data. HM supervised the study methodology, curated and interpreted the data. All authors reviewed and edited the final manuscript.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Map disclaimer The inclusion of any map (including the depiction of any boundaries therein), or of any geographic or locational reference, does not imply the expression of any opinion whatsoever on the part of BMJ concerning the legal status of any country, territory, jurisdiction or area or of its authorities. Any such expression remains solely that of the relevant source and is not endorsed by BMJ. Maps are provided without any warranty of any kind, either express or implied.

Competing interests None declared.

Patient and public involvement Patients and/or the public were involved in the design, or conduct, or reporting, or dissemination plans of this research. Refer to the Methods section for further details.

Patient consent for publication Not required.

Ethics approval Not applicable.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request. The data produced by this study are available from the corresponding author upon reasonable request.

ORCID iD

Danielle N Poole http://orcid.org/0000-0002-9845-3571

REFERENCES

1 International Committee of the Red Cross. Rule 28. medical units; n.d.
2 International Committee of the Red Cross. Protocol additional to the Geneva conventions of 12 August 1949, and relating to the protection of victims of non-International armed conflicts (protocol II). Geneva International Committee of the Red Cross; 1977.
3 International Committee of the Red Cross. Protocol additional to the Geneva conventions of 12 August 1949, and relating to the protection of victims of international armed conflicts (protocol I). Geneva International Committee of the Red Cross; 1977.
4 International Committee of the Red Cross. Geneva convention for the Amelioration of the condition of the wounded and sick in armed forces in the field (first Geneva convention); 1949.
5 International Committee of the Red Cross. Geneva convention for the Amelioration of the condition of the wounded, sick and shipwrecked members of armed forces at sea (second Geneva convention); 1949.
6 International Committee of the Red Cross. Geneva convention relative to the protection of civilian persons in time of war (fourth Geneva convention); 1949.

7 World Health Organization. WHO appalled by latest attack on Indonesian hospital in Gaza; n.d.
8 Pham PN, Vinck P, Grace R, *et al*. Strategic documentation of violence against Healthcare: towards a methodology for accountability. *World Health Popul* 2016;16:31–7.
9 Poole DN, Raymond NA, Khoshnood K. Satellite imagery identifies deliberate attacks on hospitals. *Nature* 2023;618:30.
10 Raymond NA, Davies BI, Card BL, *et al*. While we watched: assessing the impact of the satellite sentinel project. *Georget J Int Aff* 2013;14:185–91.
11 Problems from Hell, solution in the heavens?: identifying obstacles and opportunities for employing Geospatial technologies to document and mitigate mass atrocities. *Stability* 2013;2:53.
12 UN General Assembly. Rome statute of the International criminal court. Hague Neth Int Crim Court; 1998.
13 Qerimi Q. The earth–space alliance in preventing and punishing mass murder crimes: documenting and prosecuting International crimes through aerial satellite evidence. *Int J Law Inf Technol* 2022;30:135–50.
14 Freeman L. Digital evidence and war crimes prosecutions: the impact of digital technologies on international criminal investigations and trials. *Fordham Intl LJ* 2017;41:283.
15 International Bar Association Criminal Court Programme. Evidence matters in ICC trials; 2016.
16 Singh A. Review article digital change detection techniques using remotely-sensed data. *Int J Remote Sens* 1989;10:989–1003.
17 Gaza Strip. UNRWA. Available: https://www.unrwa.org/where-we-work/gaza-strip [Accessed 20 Nov 2023].
18 Openstreetmap; n.d.
19 Office for the Coordination of Humanitarian Affairs. State of Palestine - health facilities; n.d.
20 Health Cluster, Occupied Palestinian Territory WHO. Health facilities in the Gaza strip; 2018.
21 ESRI. ArcGIS desktop; n.d.
22 United Nations Institute for training and research. four years of human suffering: the Syria conflict as observed through satellite imagery; 2014.
23 StataCorp. Stata statistical software: release 17.0; 2022.
24 United Nations Satellite Centre. Gaza Strip comprehensive damage assessmentUNOSAT, Nov 26, 2023.
25 Miyamoto K, Shinde R, Das S, *et al*. Remote sensing based structural damage assessment to determine probable shelter needs in the Gaza strip Miyamoto International, Inc; 2024.
26 Rimawi R, Madani N. Gaza's broken health-care system is compounding the risk of disease. *Nature* 2023;623:32. Available: https://doi.org/10.1038/d41586-023-03349-z
27 Moussally K, Abu-Sittah G, Gomez FG, *et al*. Antimicrobial resistance in the ongoing Gaza war: a silent threat. *The Lancet* 2023;402:1972–3. Available: https://doi.org/10.1016/S0140-6736(23)02508-4
28 Rimawi R, Madani N. Gaza's broken health-care system is compounding the risk of disease. *Nature* 2023;623:32.
29 Moussally K, Abu-Sittah G, Gomez FG, *et al*. Antimicrobial resistance in the ongoing Gaza war: a silent threat. *Lancet* 2023;402:1972–3.
30 SSA Home | Index, Available: https://extranet.who.int/ssa/Index.aspx
31 International Committee of the Red Cross. Discontinuance of protection of civilian medical units, (1977).
32 Vittinghoff E, McCulloch CE. Relaxing the rule of ten events per variable in logistic and Cox regression. *Am J Epidemiol* 2007;165:710–8.
33 Haar R, Abbara A, Rubenstein L, *et al*. Attacks on health are war crimes and a public health catastrophe. *Lancet* 2023;402.
34 Alser O, Alser M. Urgent call for protecting health-care workers in Palestine. *Lancet* 2023;402:1746–7.
35 Yaqub S, Sparrelid E, Sampaio-Neto J, *et al*. Israel and Gaza: the killing of civilians must stop. *Lancet* 2023;402:2069–70.
36 Khwaja A, Bell I, Hadley D, *et al*. Gaza: a plea to reclaim our collective humanity. *Lancet* 2023;402.