Journal of
VASCULAR SOCIETIES
GREAT BRITAIN & IRELAND

J.Vasc.Soc.G.B.Irel. 2026;Online ahead of publication
http://doi.org/10.54522/jvsgbi.2026.249

www.jvsgbi.com

PROTOCOL

Quantifying carbon emissions associated with open lower limb revascularisation surgery: a prospective multicentre observational service evaluation protocol

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Received: 14th September 2026
Accepted: 29th October 2026
Online: 20th November 2026

Plain English Summary

Why we are undertaking this research: The NHS has committed to becoming a net zero health service by 2045, meaning it aims to greatly reduce the greenhouse gases that contribute to climate change. Surgery is responsible for a large proportion of the NHS's carbon emissions, but little is currently known about the environmental impact of many common operations. Lower limb revascularisation surgery is performed to improve blood flow to the legs in people with severe artery narrowing. More than 4,500 of these open procedures are carried out each year in the UK. However, the amount of carbon produced during these operations, and the factors that influence it, are currently unknown. This study aims to understand the carbon emissions associated with open lower limb revascularisation surgery in NHS hospitals. Surgery involves a complex pathway of care, including the use of surgical equipment and consumables, operating theatre energy and the care patients may need following their operation.

What we aim to do: By collecting information from hospitals across the UK, we hope to estimate the carbon footprint of open lower limb revascularisation surgery, identify the main contributors to these emissions and understand how they vary between hospitals and patients. We will also explore how complications and the need for further procedures may add to the overall carbon footprint. The findings will provide a baseline understanding of the environmental impact of open lower limb revascularisation surgery and help identify areas where further research and potential improvements could reduce emissions in the future.

Abstract

Introduction: The National Health Service (NHS) England aims to achieve net zero carbon emissions by 2045, yet surgery remains a major contributor to healthcare-related greenhouse gas emissions. Lower limb revascularisation surgery is a commonly performed vascular procedure covering both common femoral endarterectomy and bypass, but its carbon footprint and the factors contributing to this footprint have not been quantified. This study aims to quantify the carbon emissions associated with lower limb bypass surgery within the NHS, identify the principal contributors to these emissions, and evaluate variation according to patient, operative and centre-level factors.

Methods: This prospective multicentre observational service evaluation will be conducted across UK NHS hospitals performing open lower limb revascularisation surgery. The study consists of three sequential phases: (1) life cycle assessment of consumables used during lower limb bypass procedures; (2) collection of centre-level information regarding theatre characteristics, energy sources and sterilisation practices; and (3) prospective collection of patient demographics, comorbidities, operative details and consumable usage. Data from all three phases will be combined to estimate total carbon emissions for individual procedures, expressed as kilograms of carbon dioxide equivalent ($kgCO_2e$). Carbon emissions will be estimated using life cycle assessment methodologies and greenhouse gas accounting approaches described in previous vascular surgical research. Multivariable and mixed-effects regression models will be used to explore associations between carbon emissions and patient, operative and centre-level characteristics.

Discussion: This study will provide the first multicentre estimates of carbon emissions associated with open lower limb revascularisation surgery within the NHS. By identifying

high-emission consumables, procedural factors and regional variation in practice, the findings will support the development of targeted sustainability interventions in vascular surgery. The study will also explore regional variation in carbon emissions, the impact of patient comorbidities on emissions and estimate the associated mortality cost of carbon emissions. All of this will provide evidence to inform future strategies aimed at reducing the environmental impact of surgical care.

Key words: sustainability, vascular surgery, emissions

Introduction

Background and rationale

Climate change represents one of the most significant global health challenges of the 21st century. National legislation in the form of the Climate Change Act 2008 commits the UK to becoming net zero by 2050.[1] The National Health Service (NHS) in England is contributing to this through its campaign for a greener NHS, with a goal of delivering a net zero service by 2045.[2] In 2019 the NHS produced 25 million tonnes of carbon dioxide equivalent (CO2e) emissions, equating to around 7% of the total UK carbon footprint for the year.[3] To meet this target, the NHS must identify emission hotspots so that interventions can be targeted where they will have most effect.

In the UK the surgical sector is responsible for the equivalent of 5.7 million tonnes of CO2e each year, accounting for nearly 23% of NHS CO2e emissions.[4] This environmental impact has consequences for human life. The mortality cost of carbon emissions in 2020 was approximated to one excess death for every 4434 tonnes of CO2e produced.[5] Taking this into consideration, it is estimated that the current surgery-related emissions could be responsible for an excess of 1285 deaths per year.[4,5]

Consumables and medical devices, together with theatre energy and the sterilisation of reusable equipment, have been described as carbon hotspots in surgery, second to anaesthetic gases.[6] Furthermore, in the UK the National Vascular Registry (NVR) has documented a continued increase in the volume of vascular procedures and the corresponding effect on healthcare resources.[7] Over 4,500 open lower limb revascularisation surgeries are performed annually. These procedures serve as a key area for targeted environmental improvement initiatives, given their significant contribution to the surgical sector and its associated carbon emissions.

This study aims to quantify the carbon emissions generated by open lower limb revascularisation surgeries and assess the impact of patient comorbidities on these emissions.

Objectives

- To capture centre-specific data on the carbon emissions produced during lower limb bypass procedures.
- To calculate how these emissions vary depending on centre or procedure undertaken.
- To identify the element of the procedures which are contributing most significantly to the carbon emissions.

Methods

Project design and setting

This is a prospective multicentre observational service evaluation designed to quantify the carbon emissions associated with lower limb bypass surgery within the NHS. The study will comprise three sequential phases: (1) life cycle assessment of surgical consumables to establish a baseline emissions model; (2) collection of centre-level information on operating theatre characteristics, energy sources and sterilisation practices; and (3) prospective collection of patient-level and operative data from participating centres (Figure 1). The study will be conducted across UK NHS hospitals performing open lower limb revascularisation surgery.

Participating centres will be recruited through the Vascular and Endovascular Research Network (VERN), with the aim of achieving geographical representation across the UK. Recruitment will seek to include centres from different regions and healthcare settings to capture variation in local practice, patient case mix and resource use. Centres will be asked to provide information on their location and approximate annual volume of eligible lower limb bypass procedures to inform recruitment and assess the feasibility of data collection. The geographical distribution of participating centres and the characteristics of the recruited sample will be reported to contextualise the findings and identify any limitations in national representativeness.

Phase 1: Life cycle assessment of surgical consumables

Phase 1 will be undertaken at Hull University Teaching Hospitals NHS Trust, building on existing carbon emissions data for surgical equipment and consumables used during open lower limb revascularisation surgery. The assessment will include personal protective equipment such as surgical gowns, hats and gloves, alongside the consumables and equipment used throughout the procedure. Consumables will be categorised and assessed using published life cycle assessment methodologies and internationally recognised greenhouse gas accounting standards.[8] The resulting inventory will establish the carbon emissions associated with individual items and inform estimates of the consumables-related carbon footprint per procedure.

The distribution of emissions across items will be described to identify those contributing disproportionately to the total procedural footprint. Items will be assessed according to their individual carbon footprint, their relative contribution to total emissions and, where

relevant, variation in their consumption. We anticipate variation in the use of consumables such as swabs and sharps between centres. However, these items should be relatively straightforward to record as scrub nurses routinely document the quantities used during procedures. As there is no universally accepted threshold for defining high-emission consumables in this context, classification into high-, medium- and low-emission categories will be data-driven. The criteria used will be transparently reported and may be informed by consultation with clinicians, sustainability leads and environmental specialists.

The findings will inform the data collection strategy for phase 3. Consumables with high individual emissions or substantial variation in use will be prioritised for prospective item-specific recording. Where items have a low individual carbon footprint and limited variation in use, consumption may be estimated using the baseline model provided that the assumptions are considered appropriate and are assessed during the validation process.

Phase 2: Centre-level assessment

Phase 2 will involve participating NHS centres recruited through VERN. Centre-level information will be collected on operating theatre characteristics, energy sources and sterilisation practices. In addition, participating centres will provide a standardised inventory of consumables used during lower limb bypass surgery, including manufacturer and product details where available, and whether items are reusable or single-use. This will allow differences in product selection and local practice to be identified and the representativeness of the baseline emissions model to be assessed.

Phase 3: Prospective multicentre data collection and validation

Phase 3 will involve prospective collection of patient-level and operative data from eligible lower limb bypass procedures at participating centres. Data will include patient characteristics, operative details, procedure duration, theatre staffing and the quantities of relevant consumables used. Products identified in the phase 1 inventory will be prioritised for detailed recording according to their estimated carbon footprint and the anticipated variability in their use.

The Hull emissions inventory will serve as the baseline model. Where participating centres use identical products, the corresponding emissions factors will be applied. Where products differ, product-specific emissions data will be sought where available. If these are unavailable, an appropriate proxy may be used, provided that the rationale and assumptions are documented. Products with materially different specifications or potentially substantial contributions to the overall footprint will be prioritised for further assessment.

To assess the transferability of the baseline model, 1–3 cases at each participating centre will undergo detailed audit, where feasible. These audits will document actual product selection and quantities used and allow comparison with the assumptions derived from the Hull assessment. Differences in product use, local practice and data availability will be recorded and considered when interpreting centre-specific estimates. The proportion of emissions estimates based on direct product-specific data, published or manufacturer-derived data, and proxy estimates will be reported where feasible.

Integration of findings and reporting

Data from the three phases will be combined to estimate the carbon emissions associated with open lower limb revascularisation surgery, identify the principal contributors to the procedural carbon footprint and explore variation between participating centres. The study will be conducted and reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[9] The findings will establish baseline estimates of carbon emissions for open lower limb revascularisation surgery and inform future interventions aimed at reducing the environmental impact of vascular surgery within the NHS.

Eligibility criteria

Eligible participants will include all adults (aged ≥18 years) undergoing their first lower limb arterial bypass procedure during the study period. Eligible procedures include common femoral endarterectomies and lower limb bypass procedures.
Patients undergoing revision bypass procedures, emergency procedures performed following previous lower limb bypass surgery or procedures where sufficient operative data cannot be collected will be excluded from analysis. Patients who subsequently undergo additional procedures related to complications of the index bypass will remain in the study for follow-up analysis.

Sample size

There are currently no published studies quantifying carbon emissions associated with lower limb bypass surgery; therefore, reliable estimates of variability are unavailable and a formal sample size calculation cannot be performed. Phase 1 data will be used to estimate the mean and standard deviation of carbon emissions for each procedure type and to inform power calculations for future hypothesis-driven studies.

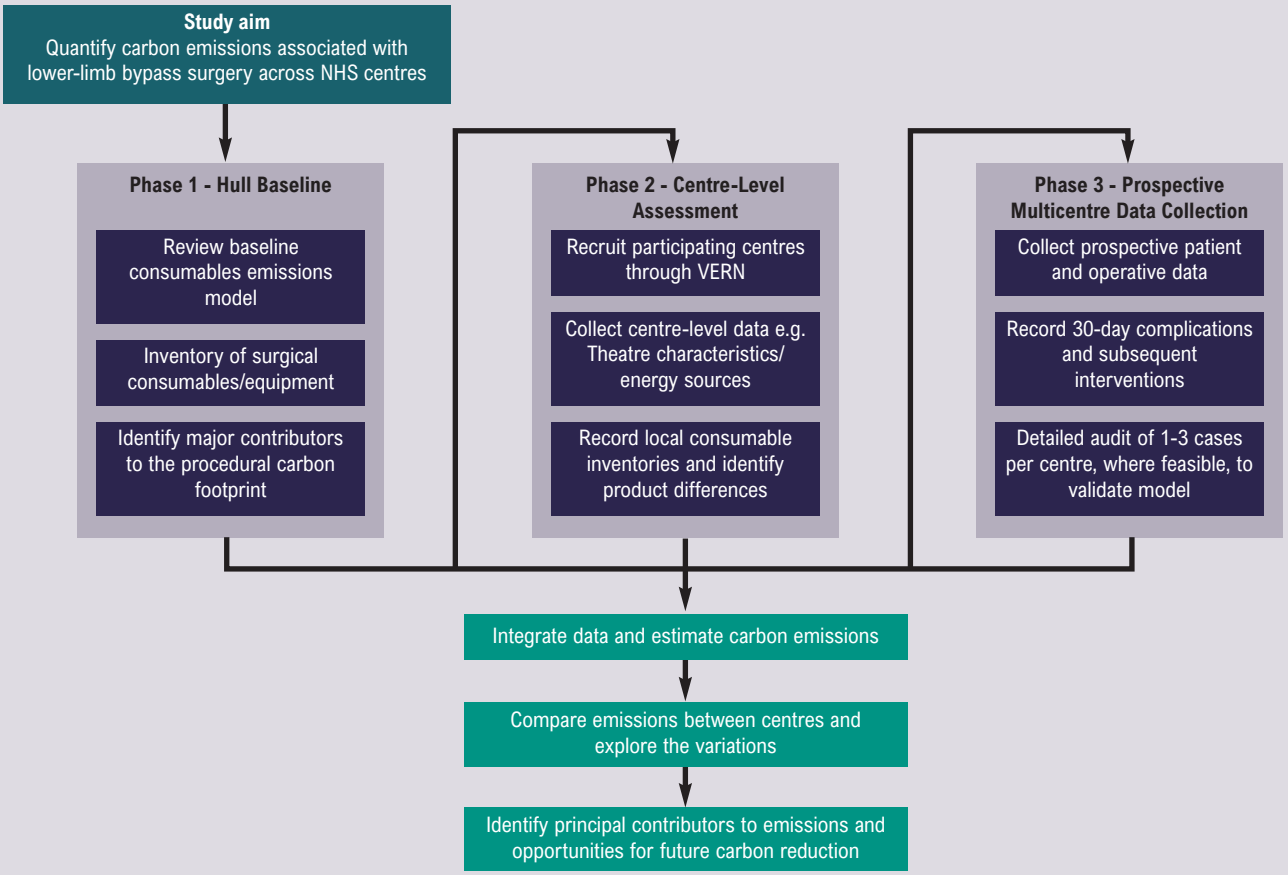
Phases 2 and 3 are therefore designed as exploratory multicentre observational evaluations. Participating centres will prospectively collect data over a 3-month period, providing sufficient information to characterise procedure-specific carbon emissions and identify important predictors of environmental impact.

Recruitment

Participating NHS centres will be recruited through VERN, as detailed above. Each participating hospital will nominate a local principal investigator responsible for study delivery and governance.

Eligible patients will be identified prospectively from vascular operating lists. Consecutive eligible procedures performed during the recruitment period will be included to minimise selection bias.

Figure 1 Overview of the three-phase study design.



As this study constitutes a service evaluation with no alteration to routine patient care, individual patient consent is not anticipated to be required, subject to local governance approval.

Interventions

No clinical intervention will be undertaken as part of this study. All patients will receive standard clinical care according to local NHS practice. The study is observational and will collect information regarding resource utilisation, operative characteristics and patient demographics without influencing clinical decision-making.

Outcomes

Primary outcome

- Total carbon emissions ($kgCO_2e$) generated during each lower limb bypass procedure.

Secondary outcomes

- Carbon emissions according to procedure type.
- Identification of consumables contributing disproportionately to procedure emissions.
- Variation in carbon emissions between participating centres.
- Association between patient demographics, comorbidities and carbon emissions.
- Association between operative characteristics (operative duration, anaesthetic technique, theatre characteristics and staffing) and carbon emissions.
- Additional carbon emissions associated with postoperative complications requiring further intervention.
- Estimated mortality cost associated with procedure-related carbon emissions using published conversion estimates.

Project timeline

The study will be conducted in three sequential phases.

Phase 1 (3 months): Central collection and life cycle analysis of consumables used during open lower limb revascularisation surgery at Hull University Teaching Hospitals NHS Trust.

Phase 2 (3 months): Collection of baseline theatre information from participating NHS centres including theatre characteristics, electricity sources and sterilisation processes.

Phase 3 (3 months): Prospective collection of patient, operative and consumable data from participating centres.

Following completion of data collection, statistical analysis, interpretation and manuscript preparation will be undertaken.

Project organisation

The study will be coordinated centrally by Hull University Teaching Hospitals NHS Trust. Overall study oversight will be provided by the Chief Investigator and supervisory research team. Participating hospitals will appoint local investigators responsible for patient identification, data collection and local governance approvals.

VERN will facilitate national recruitment, communication between centres and dissemination of study materials. A central coordinating committee will oversee study conduct, monitor data completeness and provide support throughout the study period.

Data collection and follow-up

Data will be collected prospectively using standardised electronic case report forms hosted on a secure central database. Information collected will include patient demographics, comorbidities, ASA grade, operative details, anaesthetic technique, operative duration, staffing, theatre characteristics and consumable use.

Phase 1 consumable data and phase 2 theatre information will subsequently be combined with phase 3 patient-level data to calculate the estimated carbon emissions associated with each individual procedure. The geographical location of each participating centre and relevant centre-level characteristics will be recorded to support comparisons of carbon emissions, patient case mix and clinical practice between centres. These data will help explore whether observed variation may be associated with geographical differences in the populations served, local practices or healthcare infrastructure.

Patients requiring subsequent procedures following complications of their index operation will have additional operative data collected to quantify the associated environmental impact.

- Follow-up period: 30 days from the index bypass procedure.
- Complications recorded: wound or surgical site infection, wound breakdown or delayed healing, graft thrombosis/occlusion, bleeding and other clinically significant postoperative complications.
- Resource use: unplanned readmissions, returns to theatre, endovascular reinterventions and other relevant procedures.
- Community care: not routinely recorded.

Patient comorbidities will be collected to explore associations between patient case mix and procedural carbon emissions, and to investigate whether differences in comorbidity profiles between participating centres contribute to observed variation in emissions. This will help contextualise comparisons between centres and support more detailed analysis of the national dataset including potential differences in the characteristics of patients undergoing surgery across geographical locations.

Data management

All collected data will be pseudonymised prior to entry into the central study database. No directly identifiable patient information will be transferred between participating centres.

The database will be password-protected and accessible only to authorised study personnel. All data handling will comply with the UK General Data Protection Regulation (GDPR), the Data Protection Act 2018 and local NHS information governance policies. Data will be securely stored for the period required by institutional policy before confidential destruction.

Data validation

Data quality will be maintained through predefined data collection guidance, mandatory database fields and automated range and logic checks where appropriate.

The central study team will undertake regular reviews of submitted data to identify inconsistencies, missing information and potential errors. Queries will be returned to local investigators for clarification before database lock. Random audits of submitted records may also be undertaken to ensure data accuracy and completeness.

Statistical methods

Continuous variables will be summarised using mean and standard deviation or median and interquartile range depending on data distribution. Categorical variables will be reported as frequencies and percentages.

Carbon emissions will be reported overall and according to procedure type. Comparisons between procedures will be performed using the Student's t-test, one-way analysis of variance (ANOVA) or non-parametric equivalents where appropriate. Where the number and distribution of participating centres permit, variation in estimated carbon emissions will be explored by geographical location and centre-level characteristics. Findings will be interpreted in the context of the distribution of the participating centres and will not be assumed to represent national variation where geographical coverage is limited.

Associations between carbon emissions and patient age, sex, body mass index, comorbidities, ASA grade, operative duration, anaesthetic technique, theatre characteristics and postoperative complications will be explored using multivariable linear regression. Given the multicentre design, mixed-effects regression models incorporating study centre as a random effect will be considered to account for clustering.

Variable selection will additionally be explored using LASSO and elastic net regression techniques. Model assumptions will be assessed using residual diagnostics and multicollinearity will be evaluated using variance inflation factors.

Missing data will be examined to determine the pattern and mechanism of missingness. Multiple imputation using chained equations will be considered where appropriate, with sensitivity analyses comparing imputed and complete case datasets. Statistical significance will be defined as a two-sided P value of <0.05. Statistical analyses will be performed using IBM SPSS Statistics (Version 28) and R statistical software where appropriate.

Data monitoring

As this study is an observational service evaluation with no investigational intervention, a formal independent Data Monitoring Committee will not be established.

The central coordinating team will monitor study progress through regular review of recruitment, data completeness and data quality across participating centres. Any protocol deviations or significant data quality concerns will be addressed in collaboration with local investigators.

Harms

No additional risks or harms to participants are anticipated as the study does not alter routine clinical care or require any additional investigations or interventions.

The principal risk relates to data confidentiality. This will be minimised through pseudonymisation of all patient information, secure electronic data storage and restricted database access.

Ethics and dissemination

This study is designed as a multicentre service evaluation and is not expected to require review by an NHS Research Ethics Committee. The study classification will be confirmed using the Health Research Authority (HRA) decision tool, and approval will be obtained through local clinical governance processes at each participating NHS organisation before study commencement.

All collected data will be handled in accordance with the UK General Data Protection Regulation (GDPR), the Data Protection Act 2018 and NHS information governance requirements. Patient confidentiality will be maintained through pseudonymisation of all collected data prior to central analysis.

Study findings will be disseminated through presentation at national and international vascular and sustainability conferences and publication in peer-reviewed scientific journals. Results will also be shared with participating centres and relevant NHS sustainability programmes to inform future environmental improvement initiatives.

Discussion

This service evaluation seeks to understand carbon emissions associated with open lower limb revascularisation surgeries within the NHS. By collecting data from multiple centres across the UK, we aim to identify recurring key areas where targeted green interventions could reduce carbon emissions. Highlighting areas with high carbon emissions values would not only allow targeting of green strategies but the data collected in this study would allow assessment of the effectiveness of these interventions in future studies. If the consumables that have a significant impact on carbon emissions values are generic to other surgeries – for example, gowns, gloves and suturing material – the findings of this study could have a much wider-reaching impact beyond vascular surgery. As there are a range of different lower limb bypass surgeries, it is important to analyse these individually so that future work can efficiently target only problematic areas/operations.

KEY MESSAGES

- Surgery contributes substantiality to NHS carbon emissions
- We need to identify areas for improvement before we can make changes.
- The findings of this study could reach beyond vascular surgery alone.

Another key consideration is the potential for regional variation in resource consumption and carbon emissions. By conducting this service evaluation across multiple NHS centres we will have the opportunity to compare how different hospitals use resources and contribute to carbon emissions. Differences in operating theatre efficiency, staff training, local protocols for consumables and energy sources could all influence carbon emissions. Regional variation analysis will help us identify best practices and areas for improvement. Theoretically this would allow for more cohesive consumable use and energy consumption across the NHS.

The secondary aim of this study is to assess the effect of patient comorbidities on the carbon emissions generated during surgery. Obesity, diabetes and cardiovascular disease are all examples of comorbidities that may require more complex interventions, longer operating times and hospital stays and increased resource use. By collecting clinical data, this study will allow us to assess whether certain patient demographics are associated with higher carbon emissions.

Finally, this study would allow us to assess the mortality cost associated with carbon emissions generated from open lower limb revascularisation surgery.

Conclusion

The data collected from this service evaluation will provide crucial insights into the carbon emissions generated by lower limb bypass surgeries. Through identifying areas of high resource consumption and carbon emissions, evaluating the impact of patient comorbidities and exploring regional variations, it will help us develop targeted green interventions in order to reduce the carbon footprint of surgical interventions. Furthermore, understanding the mortality cost of these emissions will help reinforce the argument for more sustainable practices within the NHS. Ultimately, this study provides a foundation for future research that will evaluate the effectiveness of green interventions.

Conflict of Interest: The investigators declare no financial or other conflicts of interest relevant to this study.

Funding and study support: The study has received £3000 in funding from the Vascular and Endovascular Research Network (VERN) to support delivery of the project. In addition to financial support, VERN will facilitate networking and engagement with participating vascular centres and provide protocol overview and support. VERN will assist with multicentre study engagement and dissemination through its national vascular research network. VERN will not have authority over

the collection, analysis or interpretation of study data or the decision to submit the study findings for publication. Responsibility for the conduct of the study, data analysis, interpretation of results and preparation of resulting publications will remain with the Chief Investigator and study team.

Coordinating centre: Hull University Teaching Hospitals NHS Trust will act as the coordinating centre for the study. Overall study coordination will be undertaken by the Chief Investigator and study team, with participating centres responsible for local study delivery, data collection and completion of applicable local governance requirements.

Sponsorship: This study has no external study sponsor. The study is being undertaken as a multicentre observational service evaluation, with study classification and applicable governance requirements to be confirmed through the appropriate Health Research Authority and local NHS governance processes prior to commencement.

Study registration: This study has been confirmed as a multicentre service evaluation and does not constitute a clinical trial. Prospective registration in a clinical trial registry is therefore not required. The study will be conducted in accordance with applicable local clinical governance and information governance requirements at each participating NHS organisation.

Reviewer acknowledgement: *JVSGBI* thanks Becky Sandford, Guy's and St Thomas' NHS Trust & Kings College London and Nina Al-Saadi, University Hospitals of Birmingham NHS Foundation Trust for their contribution to the peer review of this work.

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