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ORIGINAL RESEARCH ARTICLE

Uncovering the carbon cost: Environmental impact of free flap reconstruction procedures in the UK

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ABSTRACT

Introduction: Free flap reconstruction procedures are renowned for their duration and the requirement for many staff and large quantities of equipment. This single-centre cross-sectional study aimed to quantify the total emissions related to two such procedures carried out at a district general hospital.

Methods: One deep inferior epigastric perforator (DIEP) free flap procedure and one anterolateral thigh (ALT) free flap procedure, both carried out in February 2024, were analysed. Data related to staff transport, anaesthetic duration, mass of disposable equipment, quantity of reusable surgical equipment and consumption of electricity and heating for the relevant theatre areas were collected. Emissions were calculated using UK government conversion factors and classified by scope and contributory element as per the Greenhouse Gas Protocol.

Results: Total emissions were estimated at 385.5 kgCO_2eq for the DIEP and 369.6 kgCO_2eq for the ALT. Scope 1 emissions related to heating, atmospheric release of general anaesthetic and incineration of waste accounted for 33.7% of DIEP emissions and 35.6% of ALT emissions. Scope 2 emissions related to the use of grid electricity accounted for 44.8% of DIEP emissions and 46.7% of ALT emissions. Scope 3 emissions related to staff transport, cleaning of reusable equipment and the supply chain for disposable equipment accounted for 21.5% of DIEP emissions and 17.7% of ALT emissions.

Conclusion: Significant reductions in emissions may be achievable without significant infrastructural changes through initiatives to reduce staff transport by single-occupancy car, improving the energy efficiency of the theatre areas and reducing the use of single-use surgical equipment.

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Introduction

Human-driven climate change represents one of the greatest threats to global health in the 21st century [1]. The negative impacts on human health are expected to occur through multiple channels, including an increase in the distribution of vectors carrying tropical diseases such as malaria [2], water and food insecurity [3, 4], worsening air pollution [5], direct effects of extreme weather events [6, 7] and the loss of currently inhabited land due to extreme weather and rising sea levels thrusting millions into homelessness and multigenerational ill physical and mental health [8–10].

The provision of modern healthcare is itself a significant contributor to climate change, representing over 5% of the UK's total carbon footprint [11], with similar levels of contribution seen in other healthcare systems globally [12]. Healthcare systems have a collective responsibility to mitigate their carbon footprint on every level, from the individual staff member to macro-scale policies governing systemic priorities at regional, national and international levels. National Health Service England has a stated target of becoming the first national health service to produce zero net emissions of greenhouse gases [13], with this commitment to net zero being enshrined in law in England in the Health and Care Act 2022 [14]. In the UK, the NHS has divided its actions towards net zero into four major action areas: upgrading current hospitals, building new, efficient hospitals, optimising building usage and on-site renewable energy generation [13]. Their plan acknowledges a shortfall in the planned reduction of emissions, which must be filled through research and innovation. A key component of this research and innovation should be to identify new areas amenable to the reduction of emissions. Measuring the emissions of healthcare activities on multiple levels is essential to assess the scope to reduce emissions of a given activity and to assess the efficacy of any intervention made. Increasing the granularity of available data describing emissions of healthcare activities will improve the accuracy of estimates at all levels and aid the effective planning of new policies and initiatives.

The carbon footprint of human activity can be summarised and expressed as a mass (kg) of carbon dioxide (CO_2) equivalents (kgCO_2eq). This measure represents the total warming capacity of all the greenhouse gases attributable to a particular activity, including CO_2 and non-CO_2 components such as methane, nitrous oxide and chlorofluorocarbons. Carbon footprints have been estimated in surgery at multiple levels, from individual procedures [15–18], to surgical subspecialties [19, 20] and entire surgical departments [21]. Within plastic and reconstructive surgery, free flap reconstructions are well-known for their long duration and need for many staff

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members and large quantities of equipment. To our knowledge, assessment of the carbon footprint of such procedures has not previously been reported.

We aimed to estimate the carbon footprints of two free flap reconstruction procedures in $kgCO_2eq$, classify these emissions according to the three scopes defined by the Greenhouse Gas Protocol [12] and identify areas susceptible to improvement.

Materials and methods

This cross-sectional study was conducted in February 2024 at Bedford Hospital, a district general hospital in the United Kingdom. NHS Health Research Authority guidance indicated that this study did not require research ethics committee review or approval. This study was carried out in accordance with the relevant principles of the Declaration of Helsinki.

Direct observation and recording of data were performed during two free flap reconstruction procedures – one Deep Inferior Epigastric Perforator (DIEP) flap and one Anterolateral Thigh (ALT) flap. 2022 UK. Department for Business, Energy & Industrial Strategy (DBEIS) conversion factors were applied to the raw data through multiplication to calculate the carbon footprint in $kgCO_2eq$ [22]. Data were collected, and calculations to estimate emissions were performed using IBM SPSS v28. The total carbon footprint was classified through consideration of contributory factors under three scopes, as defined by the Greenhouse Gas Protocol [12]. The duration of heating (and electricity) consumption attributable to the procedure was both taken as 24 hours due to the inability to perform any other procedures in the relevant theatre on that day.

Scope 1 comprises direct emissions related to organisational activities, and in this context included the incineration of waste (disposable equipment and tissue) from the procedure, burning of fossil fuels for heating of hospital buildings, the atmospheric release of volatile anaesthetics and release of greenhouse gases in the surgical plume from use of diathermy. The mass of disposable medical equipment and tissue generated was assumed to be equal to the mass of waste for incineration at the end of each procedure, measured using digital scales. Emissions related to the disposal of this waste were calculated with the DBEIS conversion factor of 0.02 $kgCO_2eq$ per kg for the transport and incineration of mixed industrial/commercial waste, including metal, plastic, paper and biowaste. The hospital estates department provided data describing the total heating consumption of the hospital for the relevant month and the proportion of building surface area attributable to the relevant theatre areas, allowing calculation of the mean heating consumption for these areas for a 24 hour period in the relevant month. A DBEIS conversion factor of 0.18 $kgCO_2e$ per kilowatt hour was used to calculate heating emissions related to the burning of natural gas in steam boilers. All patients were maintained under general anaesthesia using sevofluorane. The carbon footprint of volatile general anaesthesia was determined through the use of a per-hour minimum alveolar concentration conversion factor for sevofluorane of 1.58 $kgCO_2e$ per hour [23]. Emissions related to the surgical plume were unmeasurable and deemed negligible as they only comprised gases released during diathermy.

Scope 2 comprises indirect emissions related to purchased electricity. These emissions were quantified using figures derived from the central power distribution unit within the hospital and local data logging activities by the hospital estates team on specific circuits to accurately estimate the consumption of the relevant areas over a 24-h period. The theatres and recovery areas used for the procedures share circuits for their electricity supply. As a result, estimating each individual procedure's electricity consumption was not possible. Instead, the total consumption for both procedures was divided by two. A DBEIS conversion factor of 0.23 $kgCO_2e$ per kilowatt hour for UK grid energy was used to determine the scope 2 emissions.

Scope 3 comprises all other indirectly associated emissions, which, in this context, included staff and patient transport, the supply chain for the manufacture and delivery of disposable equipment and the cleaning of theatres, communal areas, linen, patient gowns, staff uniforms and reusable surgical equipment. The staff members directly involved in the procedure alongside one theatre receptionist and one nurse in each of the recovery areas and the surgical day wards were asked their mode of transport to the hospital and fuel type for the day of the procedure. Distance travelled was calculated for a round trip from the staff member's home address to the hospital, and emissions were calculated using DBEIS conversion factors per kilometre travelled according to mode of transport and fuel type. Emissions for train journeys were estimated using the figures reported for the relevant journeys by Trainline – the UK's largest train ticket purchase platform [24]. The transport of the investigator carrying out data collection (B.C.) was not included as they were not contributing to the procedure itself. Cleaning of theatres, communal areas, linen, patient gowns and staff uniforms all fall under scope 3 emissions, but all rely on electricity consumption and could not be measured independently of scope 2 emissions. Therefore, these factors are captured by the data for scope 2 emissions. The numbers of each size (small, medium and large) of autoclave equipment tray utilised for the provision of reusable surgical equipment was recorded during each procedure. The emissions related to autoclave cleaning of reusable equipment were calculated through the determination of the number of cleaning cycles undertaken and the electricity consumption related to each cycle, estimated at 7 kWh per cycle of the washer disinfector and 5 kWh per cycle of the steam steriliser, according to the manufacturer information. The mass of disposable medical equipment used was taken as equal to the total mass of waste generated. This likely resulted in a slight overestimation of the mass of disposable equipment due to the inclusion of tissue in the mass of waste generated, but this could not be segregated. The masses of different material types (paper, plastic, metal, etc.) in the total mass of disposable medical equipment used could not be discriminated. As a result, emissions related to the manufacture and delivery of this equipment were calculated using the DBEIS conversion factor of 3.12 $kgCO_2eq$ per kg for mixed plastics disposable equipment. The rate of emissions for mixed plastics is intermediate between those of paper and metal and, therefore, is likely to present a reasonable estimate of the mean rate of emissions for this element. This conversion factor only accounts for the emissions related to the production of the raw materials used in the equipment, that is the mixed plastics, rather than the emissions related to the manufacture, sterilisation and transport of the end-products. This can only be captured using a life-cycle analysis, which was not performed. As such, this element of scope 3 emissions is likely to be underestimated by this study, as explored further in the 'Limitations' section of the discussion.

Results

One DIEP flap procedure and one ALT flap procedure were analysed, involving 12 staff members each. A detailed breakdown of the emissions by scope and individual contributory elements is given in Table 1.

DIEP flap

The carbon footprint attributable to the DIEP procedure was 385.5 $kgCO_2eq$.

Table 1. Emissions classified by procedure, emissions scope and contributory element.

	DIEP		ALT	
	$kgCO_2eq$	% of total	$kgCO_2eq$	% of total
Scope 1				
Incineration of waste	0.2	0.1	0.3	0.1
Burning of natural gas for heating of buildings	116.9	30.3	116.9	31.6
Atmospheric release of volatile anaesthetics	12.9	3.3	14.3	3.9
Atmospheric release of surgical plume	Negligible	Negligible	Negligible	Negligible
Subtotal	130.0	33.7	131.5	35.6
Scope 2				
Purchase of electricity	172.6	44.8	172.6	46.7
Subtotal	172.6	44.8	172.6	46.7
Scope 3				
Staff transport				
Petrol vehicle				
Small	0.0	0.0	5.5	1.5
Medium	15.4	4.0	9.1	2.5
Large	7.4	1.9	2.1	0.6
Diesel vehicle				
Small	0.3	0.1	0.0	0.0
Medium	0.0	0.0	0.0	0.0
Large	17.0	4.4	1.1	0.3
Plug-in hybrid				
Small	0.0	0.0	0.0	0.0
Medium	0.0	0.0	0.5	0.1
Large	0.2	0.1	0.5	0.1
Electric vehicle				
Small	0.0	0.0	0.0	0.0
Medium	0.0	0.0	0.0	0.0
Large	0.0	0.0	0.0	0.0
Train	1.1	0.3	2.7	0.7
Autoclave cleaning of surgical equipment	2.8	0.7	2.8	0.8
Disposable equipment supply chain	38.7	10.0	41.2	11.1
Subtotal	82.9	21.5	65.5	17.7
Total	385.5	100.0	369.6	100.0

DIEP: deep inferior epigastric perforator; ALT: anterolateral thigh.

Scope 1 emissions were estimated at 130.0 $kgCO_2eq$ (33.7% total emissions). 89.9% (116.9 $kgCO_2eq$) of scope 1 emissions were from the burning of natural gas for heating of the theatre areas. Atmospheric release of sevofluorane from the general anaesthesia contributed 12.9 $kgCO_2eq$ (9.9% scope 1 emissions and 3.3% total emissions).

Scope 2 emissions from the purchase of grid electricity were estimated at 172.6 $kgCO_2eq$ (44.8% total emissions) and were the largest contributor to DIEP emissions of the three scopes.

Scope 3 emissions were estimated at 82.9 $kgCO_2eq$ (21.5% of total emissions). Most of the scope 3 emissions were related to staff transport to and from the hospital (41.4 $kgCO_2eq$, 49.9% scope 3 emissions) and the supply chain for disposable surgical equipment (38.7 $kgCO_2eq$, 46.7% scope 3 emissions).

ALT flap

The carbon footprint attributable to the ALT procedure was 369.6 $kgCO_2eq$.

Scope 1 emissions were estimated at 131.5 $kgCO_2eq$ for the ALT (35.6% total emissions). 88.9% (116.9 $kgCO_2eq$) of scope 1 emissions were from the burning of natural gas for heating of the theatre areas. Atmospheric release of sevofluorane from the general anaesthesia contributed 14.3 $kgCO_2eq$ (10.9% scope 1 emissions and 3.9% total emissions).

Scope 2 emissions were the largest contributor to ALT emissions at 172.6 $kgCO_2eq$ (46.7% total emissions).

Scope 3 emissions contributed 65.5 $kgCO_2eq$ (17.7% of total emissions). The largest component of scope 3 emissions for the ALT flap was the supply chain for disposable surgical equipment (41.2 $kgCO_2eq$, 62.9% scope 3 emissions and 11.2% total emissions). Staff transport contributed 21.5 $kgCO_2eq$ (32.8% scope 3 emissions and 5.8% total emissions).

Discussion

This is the first study to assess the carbon footprint of free flap reconstruction procedures, to the authors' knowledge. Both procedures were of similar total duration and general anaesthetic duration. The estimated total emissions of each procedure were similar.

Similar studies in countries with high levels of economic development have assessed the emissions of the following individual surgical procedures: caesarean section (37 $kgCO_2eq$) [16], skin cancer primary excision (clinic-based – 29 $kgCO_2eq$, hospital-based – 81 $kgCO_2eq$) [18], cataract surgery (182 $kgCO_2eq$) [15] and hysterectomy (vaginal – 285 $kgCO_2eq$, abdominal – 293 $kgCO_2eq$, laparoscopic – 562 $kgCO_2eq$, robotic – 814 $kgCO_2eq$) [17]. Direct comparisons are not recommended due to differences in study methodology, geographical setting and institutional setting [25]. A study of theatres in large quaternary surgical centres in the UK, Canada and the USA over the complete range of procedures performed in 1 year estimated the average emissions of an individual surgery to be 173 $kgCO_2eq$ in the UK centre, 146 $kgCO_2eq$ in the Canadian centre and 232 $kgCO_2eq$ in the USA centre [21]. These estimates broadly align with the total estimated emissions of free flap reconstruction in this study.

Scope 1 emissions represented approximately one third of total emissions for both procedures. The largest constituent of scope 1 emissions was the burning of natural gas for the heating of the relevant areas of the hospital. This study was undertaken in February 2024 in the UK, with average ambient atmospheric temperatures being significantly below safe working temperatures, thus necessitating significant levels of heating. The total monthly consumption of natural gas for the hospital boiler house over 12 months from April 2022 to March 2023 (Supplementary Material, Table 1) demonstrates that the average monthly consumption over the year is 22.7% lower than the February consumption. When adjusting for this, the total emissions are reduced by 26.5 $kgCO_2eq$ for each procedure, corresponding to an approximate 7% reduction in total emissions.

The retrofitting of a more efficient hospital heating system would likely be extremely costly and might not lead to a net reduction in emissions over the lifespan of the hospital buildings before a total demolition and rebuild are necessary anyway. Instead, new hospital building projects should be prioritised and fitted with efficient gas boilers, ground or air source heat pumps or other systems with lower running emissions than the systems currently in place. In the same way, improving the insulation efficiency of new hospital buildings, and designing entry/exit points with heating buffer areas could significantly reduce heating expenditure. Considering the disposal of waste, its disposal using incineration is unlikely to be modifiable due to its biohazardous nature and obligations under the Human Tissue Act 2004 in the UK and similar legislation internationally.

The release of volatile anaesthetics into the atmosphere was responsible for 3–4% of total emissions. The environmental impact of these emissions is likely to be greater than the figure expressed in $kgCO_2eq$ implies due to the role of fluorinated compounds in the depletion of the ozone layer [23]. In the UK, there has been a systemic effort to reduce the use of desfluorane in particular, due to its potent greenhouse effect (2,540 times the effect of the same quantity of CO_2) [26]. Sevofluorane has a much weaker greenhouse effect in comparison once released into the atmosphere [23], and when used in combination with vapour capture technologies to reduce atmospheric release of the gas, it can have a carbon footprint as low as total intravenous anaesthesia with agents such as propofol [26]. However, the production method of the volatile anaesthetics makes a big difference to their total attributable emissions, with sevofluorane synthesised from tetrafluoroethylene having a similar carbon footprint to even desfluorane [26]. This highlights the need for conscientious choice of procurement pathways for all surgical and anaesthetic equipment.

Scope 2 emissions related to the purchase of electricity from the grid were the largest component of emissions in both procedures. National-level increases in the proportion of renewables in the grid energy mix will lead to reductions in scope 2 emissions for all human-related activities, including healthcare. The installation of on-site renewable energy production methods such as solar or wind may also represent a reasonable way to reduce scope 2 emissions, particularly in areas where the grid mix involves a large proportion of fossil fuel-burning modes of electricity generation.

A multicentre study conducted in the UK, USA and Canada analysed scope 2 emissions with a higher level of granularity than in the present study, finding that heating, ventilation and air conditioning systems in theatre areas accounted for over 90% of scope 2 emissions [21]. They demonstrated a 50% reduction in these emissions at the Canadian centre when they reduced the ventilation flow rate in theatres overnight and on weekends when out of use. This intervention is likely to be achievable without major retroactive modifications to heating, ventilation and air conditioning systems and could, therefore, result in significant improvements in emissions related to surgical practice at many centres. Similar interventions related to the climate-conscious control of existing systems, such as lighting, may also have the potential to reduce emissions without the need to replace current equipment. Nevertheless, when equipment or facilities are due for refurbishment or replacement, energy-efficient options should be prioritised where financial constraints allow.

When considering scope 3 emissions, the impact of fossil fuel-burning vehicles, particularly diesel vehicles, is clearly seen. One large diesel vehicle represented 4.4% of the total emissions in the DIEP and can account for the majority of the difference in total emissions between DIEP and ALT. In the UK, national measures including the planned ban on new petrol and diesel vehicles from 2035 will lead to a reduction in the impact of these highly polluting vehicles [27]. In this study, many staff members lived within 2 km of the hospital but still drove in single-occupancy vehicles rather than walking or taking public transport. This reflects the national picture, with most NHS staff commuting to work in single-occupancy vehicles [28]. Staff should be disincentivised from making short journeys by car where possible. This could be achieved at the level of the individual hospital through multiple interventions such as proportional increases in the cost of parking permits for more polluting vehicles and for staff living close to the hospital, increased availability of salary-sacrifice schemes for the purchase of cycling equipment and hybrid or electric vehicles, and agreements with local public transport companies to provide free staff transport. Many staff need to travel between sites, making cars the most practical travel method overall. The need for a car for these journeys likely increases their use of cars for transport to and from their primary site of work, which may be otherwise commutable through means other than a single-occupancy car [29]. Shuttle services between hospital sites could be set up, which may serve to reduce the reliance on single-occupancy vehicles for inter-site journeys and reduce the number of staff using these vehicles whatsoever, with potentially significant reductions in staff transport emissions overall.

Scope 3 emissions also include the supply chain for disposable equipment. The calculated emissions for this element are likely to have been underestimated in this study, as explored further in the 'Limitations' section. A previous UK study performed a full life-cycle analysis of all the disposable and reusable surgical products (anaesthetic products excluded) used in five common procedures: carpal tunnel decompression, inguinal hernia repair, total knee arthroplasty, laparoscopic cholecystectomy and tonsillectomy [30]. They found that the emissions attributable to the supply chain for the production of disposable products represented 54% of the full life-cycle emissions of all the products used, with reductions of up to 20% in procedural emissions possible with a switch to reusable products where they are available on the market. Whilst the emissions related to the cleaning of reusable equipment were captured under scope 2 emissions due to methodological constraints in this study (see 'Materials and Methods' section), the potential for the reduction of these emissions will be discussed here. The same study mentioned earlier estimated that optimising the loading of the washer disinfector and steam steriliser machines, increasing the use of individually wrapped pieces of equipment which are not always needed rather than including them in the standard operating sets and switching from plastic-based wrapping to cotton-based wrapping for these sets could reduce product-related emissions by another 10% [30]. All of the suggested changes to the use of equipment in scope 3 could be readily performed without major infrastructural changes and could have a significant impact on the total procedural emissions.

Future studies should aim to include greater numbers of procedures to establish a more robust mean measurement of the emissions related to free flap reconstruction, particularly with regard to procedural factors such as the use and disposal of single-use medical equipment. Additionally, future studies should aim to compare emissions between centres of differing geography and modernity over longer periods of time. In large cities where the cost of living is higher and there is an infrastructural emphasis on walkability and public transport, emissions related to all healthcare activities may be significantly reduced. Centres in countries with hotter climates than the UK may demonstrate significant differences in the proportion of emissions related to heating, with emissions from air conditioning likely to be increased instead. Separately, more modern centres may demonstrate reductions in scope 1 emissions related to heating due to the use of more efficient systems, and total emissions may even be reduced by carbon offset initiatives such as carbon capture.

Limitations

This is a small study at one centre, analysing only two individual procedures. This was due to the logistical difficulty of having one member of staff available to conduct data collection whilst not having any clinical responsibilities related to the procedure. This limitation is significant, and this study should only be interpreted as an initial analysis to prompt further research.

Cleaning of theatres, communal areas, linen, patient gowns and staff uniforms had to be included under scope 2 despite they are true scope 3 emissions, as discussed in the 'Materials and Methods' section. This resulted in an overestimation of scope 2 emissions and an underestimation of scope 3 emissions, the magnitude of which is not clear. However, this limitation will not have affected the total emissions figure.

Data were collected for two procedures conducted on the same day in February 2024, when the UK is colder than its yearly average ambient temperature. As discussed, scope 1 emissions related to heating were higher than the monthly average over 12 months. Collecting data over 12 months would allow the potential confounding impact of the ambient temperature on total emissions to be accounted for.

The accuracy of the scope 2 emissions from the use of purchased grid electricity may be limited by our method of estimation. We estimated these emissions by measuring the total 24 hour electricity emissions of the specific relevant areas through localised electricity metering and figures from the hospital's central power distribution unit. The localised metering activities could not take place on the day of the procedures due to logistical constraints. Instead, the electricity usage of these areas was monitored over five consecutive weekdays when theatres were in daily use with full-day operating lists (similar total list time to the free flap reconstructions) and used to derive an average 24 hours of consumption. As such, the estimated scope 2 emissions more accurately represent the scope 2 emissions attributable to a non-specific full-day operating list in these theatres for a range of procedures rather than for free flap reconstructions specifically.

Emissions related to the use of disposable equipment are very likely to be underestimated in this study as the available conversion factors only capture the emissions related to the production cycle of the raw materials, not the manufacture, sterilisation and transport of the end-products. Accurate analysis of these emissions would require full life-cycle analysis, which was not practically achievable in this small study. Previous work has demonstrated the full life-cycle emissions of one single-use laryngeal mask airway alone to be 11.3 kgCO_2eq [31]. One airway represents a very small proportion of the total waste generated, yet 11.3 kgCO_2eq represents over 25% of the estimated disposable product supply chain emissions in this study, indicating the significant degree to which these scope 3 emissions are likely to have been underestimated.

This study was only able to capture the emissions related to the procedure itself rather than the patient's overall treatment pathway, of which the surgery was only one element. Further studies should aim to track emissions on a per-patient basis from the point of referral to the point of discharge from the service.

Conclusion

This study is the first to analyse the carbon footprint related to free flap reconstruction procedures in plastic and reconstructive surgery. We find that DIEP and ALT flaps result in similar rates of emissions, with staff transport being the greatest contributor. Initiatives to encourage less-polluting methods of transport for staff should be implemented. Other areas for improvement related to the electricity expenditure of theatre areas and the use of disposable equipment are highlighted. Future research should aim to analyse the emissions of more areas of plastic and reconstructive surgery, examine the impact of referral and follow-up pathways on emissions and explore how emissions vary in centres differing in geography and modernity.

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Declaration of interest statement

The authors declare that there are no competing interests to declare.

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