**Reducing the environmental impact of surgery on a global scale: systematic review, co-prioritisation with healthcare workers in 132 countries**

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**Supplementary tables**

**Table S1**. Search terms for systematic review

|  |  |  |
| --- | --- | --- |
|  | Search terms | Studies, n |
| 1 |  exp Carbon Footprint/ | 10917 |
| 2 |  Carbon Footprint.ti,ab. | 4966 |
| 3 |  greenhouse gas emissions.ti,ab. | 18529 |
| 4 |  exp Climate Change/ | 210664 |
| 5 |  climate change.ti,ab. | 184637 |
| 6 |  exp Global Warming/ | 44338 |
| 7 |  global warming.ti,ab. | 38597 |
| 8 |  life cycle assessment.ti,ab. | 14304 |
| 9 |  1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 | 311741 |
| 10 |  surgery.ti,ab. | 3004718 |
| 11 |  exp General Surgery/ | 57659 |
| 12 |  anaesthesia.ti,ab. | 163638 |
| 13 |  operating theatre.ti,ab. | 8861 |
| 14 |  exp Operating Rooms/ | 57907 |
| 15 |  operating room.ti,ab. | 69053 |
| 16 |  10 or 11 or 12 or 13 or 14 or 15 | 3211173 |
| 17 |  9 and 16 | 356 |
| 18 |  Carbon footprints.ti,ab. | 817 |
| 19 |  1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 18 | 311919 |
| 20 |  16 and 19 | 356 |
| 21 |  net-zero-carbon.ti,ab. | 63 |
| 22 |  1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 18 or 21 | 311944 |
| 23 |  16 and 22 | 360 |

**Table S2.** Summary of included studies from the systematic review in phase 1 and references

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Study Name** | **Study Duration** | **Patients** | **Country** | **Hospital Type** | **Study Setting** | **Study Type** | **Surgery Type** | **Description** | **Carbon Output** |
| **Scope I** |  |  |  |  |  |  |  |  |  |
| Mehta 19751 | NR | NR | UK | NR | NR | NR | NR | Scavenging systems | No reporting on impact to carbon emissions |
| Barwise 20112 | NR | NR | USA | Academic | Single centre | PCS | All surgery | Scavenging systems | Reduced waste anaesthetic scavenging flows and reduced energy costs |
| Tay 20133 | NR | 3675 | Australia | District / Community | Single centre | PCS | NR | Automated control of end-tidal gases | Reduced carbon emissions by 44% |
| Boyle 20184 | Dec 2017 - Mar 2018 | NR | UK | District / Community | Single centre | PCS | NR | Use of sevofluorane over desflorane | 81% decrease in carbon emissions from 394,126 kg to 74,004 kg |
| Belford 20195 | NR | NR | Australia | Academic | Single centre | PCS | NR | Anaesthetic Gas - reduction in desflurane use | - |
| van der Griend 20196 | Dec 2017 - Jan 2018 | 94 | Canada | Community | Single centre | RCS | Paediatric | Use of TIVA | No reporting on impact to carbon emissions |
| Zuegge 20197 | NR | NR | USA | Academic | Single centre | PCS | NR | Use of sevofluorane over desflorane | Reduction in carbon emissions by 80% - 90% |
| Caycedo-Marulanda 20208 | Jan 2017 - June 2018 | 63 | Canada | Academic | Single centre | RCS | Colorectal | Anaesthetic gas change | Carbon reduction >90% with sevofluorane |
| Richter 20209 | Jan 2017 - Dec 2018 | 20856 | Germany | Academic | Multi-centre | PCS | All surgery | Volatile anaesthetics - sevoflurane & desflurane | Reduction of two-thirds of carbon output |
| Back 202110 | Oct-20 | 58 | UK | Academic | Single centre | PCS | NR | Fresh gas flow rates in TIVA | Cost reduction of more than £8000/year |
| Carta 202111 | NR | NR | UK | District / Community | Single centre | PCS | NR | Anaesthetic Gas - reduction in desflurane use | Reduction in carbon emissions by 74% |
| Craven 202112 | NR | 280 | UK | Academic | Single centre | PCS | NR | Use of TIVA | No reporting of carbon emissions reduction |
| Herbert 202113 | Mar 2020 - May 2020 | NR | UK | Academic | Single centre | RCS | NR | Anaesthetic Gas - reduction in desflurane use | Reduction in carbon emissions by 229,082 kg |
| Jameson 202114 | NR | NR | UK | Academic | Single centre | PCS | NR | Low flow rates | No reporting on carbon emissions |
| Kirkman 202115 | Sep 2020 - Feb 2021 | NR | UK | Academic | Single centre | PCS | NR | Anaesthetic Gas - reduction in desflurane use | Reduction in carbon emissions by >34,000kg |
| Thiel 201816 | Sep 2015 - Dec 2016 | 17 | USA | Academic | Single centre | PCS | Hysterectomy | Use of desfluorane, recycling, reusable instruments; HVAC | Reducing N20 reduced carbon emissions by 25%, recycling & reusable materials by 5% |
| **Scope II** |  |  |  |  |  |  |  |  |  |
| Agrawal 201017 | Dec 2008 - Aug 2009 | 71 | India | Academic | Single centre | PCS | NR | Avoid energized equipment | - |
| Practice Greenhealth 201818 | Jan 2017 - Dec 2017 | NR | USA | NR | Multi-centre | RCS | NR | Reducing air exchange - 20 times-an-hour to 6 times-an-hour when ORs are not in use | Saved $2 million/year |
| Practice Greenhealth 202119 | Jan 2021 - Dec 2021 | NR | USA | Academic | Single centre | RCS | NR | HVAC occupancy sensers in 2 of their ORs | Reduced energy use by 25,000 kW per hour and savings of $4000 dollars per year  |
| Practice Greenhealth 202120 | Jan 2021 - Dec 2021 | NR | USA | NR | Multi-centre | RCS | NR | Replaced fluorescent lamps with LEDs in 10,500 coffers | Reduced electric consumption by 28.6 million kW per year. |
| **Scope III** |  |  |  |  |  |  |  |  |  |
| Dettenkofer 199921 | NR | NR | Germany | Academic | Single centre | PCS | NR | Reusable drapes | No reporting of carbon emissions reduction |
| DeBois 2013 22 | NR | 400 | USA | Academic | Single centre | PCS | Transplant Surgery | Diverting bypass circuits from the traditional regulated medical waste | Reduction in waste by 7.5 tons and carbon output |
| Southourn 2019 23 | NR | 44 | UK | NR | Multi-centre | PCS | Orthopaedic | Recycling waste | Reduction in carbon emissions by 75% & savings of £420,000 per year |
| Wormer 2013 24 | NR | NR | USA | Academic | Single centre | PCS | NR | Recycling waste | Reduction by 234.3 metric tons |
| Lui 2014 25 | Sep 2012 - April 2013 | 97 | Canada | Academic | Single centre | PCS | Head and Neck | Recycling waste | No reporting on impact to carbon emissions |
| McGain 2017 26 | NR | NR | Australia | District / Community | Single centre | PCS | NR | Reusable anaesthetic equipment | Increased carbon emissions by 10% |
| Sadler 201727 | NR | NR | UK | District / Community | Single centre | PCS | NR | Recycling waste | Reduction by 1500kg |
| Nesaratnam 2018 28 | Dec 2017 | 121 | UK | District / Community | Single centre | PCS | NR | Recycling | No reporting of carbon emissions reduction |
| Connolly 2019 29 | NR | NR | Australia | District / Community | Single centre | PCS | NR | Recycling waste | - |
| Jandu 202030 | NR | NR | UK | Academic | Single centre | PCS | NR | Recycling of waste | Reduction of clinical waste by 19,320 kg/year |
| Jabouri 202131 | 2019 | 62 | UK | Academic | Single centre | PCS | NR | Reusable surgery packs | Reduction of carbon emissions by 6% |
| Vozzola 2020 32 | NR | NR | USA | NR | NR | PCS | NR | Resuable gowns - compared to disposable gowns | Reduced natural resource energy consumption by 64%, greenhouse gas emissions by 66%, blue water consumption by 83%, and solid waste generation by 84% as compared with disposable gowns |
| Bhatter 2021 33 | NR | 34 | USA | Academic | Single centre | PCS | Plastics | Recycling | No reporting on impact to carbon emissions |
| Putri 2021 34 | NR | NR | UK | NR | NR | RCS | Opthalmology | Use of non-disposable instruments | No reporting on impact to carbon emissions but cost savings of £27,660 / year |
| Rizan 2021 35 | Apr 2017 - Mar 2018 | NR | United Kingdom | Academic | Single centre | RCS | NR | Steam sterilisation - Packaging reusable surgical instruments | Reduction in carbon emissions by 6% - 12% |
| Vacharathit 2021 36 | - | NR | USA | Academic | Single centre | PCS | NR | Recycling waste | - |

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**Table S3.** Summary of additional interventions identified from systematic review during Phase 1 that were combined into list from Table 2

|  |  |
| --- | --- |
|   | **Combined into final list of interventions**  |
| **Scope 1** |
| Reduce isoflurane\* | Reduce the use and wastage of anaesthetic gases |
| Increase sevoflurane | Reduce the use and wastage of anaesthetic gases |
| Increase regional anaesthesia | Reduce the use of general anaesthesia |
| Use of scavenging systems | Reduce the use and wastage of anaesthetic gases |
| Extended duration of anaesthetics circuit | Reduce the use and wastage of anaesthetic gases |
| Small canisters for gas cylinders | Reduce the use and wastage of anaesthetic gases |
| Manual vs automated ET control | Reduce the use and wastage of anaesthetic gases |
| Turning off excessive gas flows and vaporisers following an anaesthetic  | Reduce the use and wastage of anaesthetic gases |
| Careful filling of vaporisers | Reduce the use and wastage of anaesthetic gases |
| Judicious checking of all connections along the anaesthesia circuit and at the machine | Reduce the use and wastage of anaesthetic gases |
| Using properly fitting face masks and inflated endotracheal tube and laryngeal mask airway cuffs | Reduce the use and wastage of anaesthetic gases |
| **Scope 2** |
| Reducing air exchange when OR not in use | Reduce energy and water use |
| **Scope 3** |
| Reusable needle/sharp containers | Reduce consumables used |
| Steam sterilisation | Reduce energy and water use |
| No routine preoxygenation | Reduce the use and wastage of anaesthetic gases |
| Donating unused medical equipment and supplies to medical missions | Reduce consumables used |
| Using prefilled medication syringes | Reduce consumables used |
| Partnering with industry to promote greener packaging practices | Increase use of consumables that can be easily recycled |
| Reuse sterile paper for the C-arm  | Introduce reusable surgical gowns and drapes |

**Table S4.** Country of origin income group and job role of perioperative professionals and theatre managers from the global consultation surveys

|  |  |  |
| --- | --- | --- |
| **Feature** | **Round 1** | **Round 2** |
| **n=3042** | **n=5218** |
| **World Bank Country Income classification** |
| High income countries | 1,928 | 64.00% | 2923 | 56.00% |
| Low- and middle-income countries | 1085 | 36.00% | 2295 | 44.00% |
| Low-income countries | 84 | 2.80% | 282 | 5.40% |
| Lower middle-income countries | 512 | 17.00% | 986 | 18.90% |
| Upper middle-income countries | 489 | 16.20% | 1027 | 19.70% |
| Missing | 29 |   | 0 |   |
| **Respondent type** |
| Anaesthetist, consultant | 189 | 6.70% | 349 | 6.80% |
| Anaesthetist, trainee | 71 | 2.50% | 125 | 2.40% |
| Nurse | 28 | 1.00% | 59 | 1.10% |
| Operating department practitioner | 18 | 0.60% | 91 | 1.80% |
| Physician assistant | 57 | 2.00% | 233 | 4.50% |
| Surgeon, consultant | 1620 | 57.40% | 2704 | 52.40% |
| Surgeon, trainee | 826 | 29.20% | 1567 | 30.40% |
| Theatre manager / stores | 15 | 0.50% | 34 | 0.70% |
| Missing | 218 |   | 56 |   |

**Table S5.** Additional interventions suggested by perioperative healthcare professionals in first global consultation survey, later combined into the final list of interventions

|  |  |
| --- | --- |
|  | **Interventions** |
| 1 | Reducing use of printed materials/ paper |
| 2 | Reusable theatre hats |
| 3 | Reusable masks |
| 4 | Ordering restock in bulk |
| 5 | Maximising use of available theatres |
| 6 | Turning off ventilation systems at night |
| 7 | Installation of CO2 pipes instead of refillable cylinders |
| 8 | Green champions / education of theatre staff |
| 9 | Battery recycling |
| 10 | Reducing the number of people in theatre |
| 11 | Glass recycling |
| 12 | Scavenging of anaesthetic gasses |
| 13 | Using battery powered rather than wired instruments |
| 14 | Reusing warm-air blankets |
| 15 | Switching general to regional or local anaesthesia |
| 16 | Increasing day case surgery |
| 17 | Turning off ventilation systems at night |
| 18 | Installing piped gas supply rather than using cylinders |
| 19 | Reducing single use energy devices / reusing devices |
| 20 | Reducing single use staplers / reusing devices |
| 21 | Reducing use of prepacked gauze |
| 22 | Waste audits |
| 23 | Automated soap dispensers |
| 24 | low-dose protocols for angiography |
| 25 | No overshoe covers |
| 26 | Use of reusable slippers |
| 27 | Using only a single layer of gloves |
| 28 | Turning off Suction when not needed |
| 29 | Attaching fume suction to Electrocautery etc |
| 30 | Reusable, personal visors/goggles |
| 31 | Only disposing of what has to go in biohazard bins in those bins |
| 32 | Dont open anything until surgeon asks for this |
| 33 | Using cell saver |
| 34 | Resusable instruments |
| 35 | Reducing suture use |
| 36 | Reducing operating light use with using headlight |
| 37 | Use of resuable laryngoscope and oropharyngeal airways |
| 38 | Use of reusable operating light handles |
| 39 | Lowering pressure and flow of laparoscopic surgery |
| 40 | Shutting down equipment (e.g. computers |
| 41 | Using leftover suture/ equipment for training |
| 42 | Reusing sterile clothes |
| 43 | Alcohol based hand wash for surgical scrubbing (that does not require running water) |
| 44 | Running the forced air warmer on the medium flow settings (same results as high low) |
| 45 | Electronic/re-usable chest drain system (e.g. Thopaz) |
| 46 | Sharp Recyclings |
| 47 | Upcycling device packaging |
| 48 | Reusing single-use instruments |
| 49 | Reducing use of ventilated whole body suits for orthopaedic surgery |
| 50 | Using dissolvable sutures instead of metal staples to close wounds |
| 51 | Using single absorbable dressings instead of multiple pressure dressings |
| 52 | Use of biodegradable disposables (e.g. syringes) |
| 53 | Use of an electronic (rather than paper theatre booking system) |
| 54 | Reusable sharps bins |
| 55 | Reusable diathermy probes/kit |
| 56 | Reusable goggles/eyewear |
| 57 | Automatic on/off taps for handwashing |
| 58 | Reusable suction devices |
| 59 | Reusable instrument packaging |
| 60 | Only opening instruments when verified for use by surgeons |
| 61 | Reducing ease of access to high impact devices/instruments in OR |
| 62 | Reusable bedsheets and gowns for patients |
| 63 | Reusable diathermy mat |
| 64 | Reusable external fixators |
| 65 | Fully digital electronic patient and imaging records |
| 66 | Reusable marking pens |
| 67 | Powering theatres using solar panels |
| 68 | Computers switched off overnight + energy saving in day |
| 69 | Use of a smoke evacuation system |
| 70 | Electronic/AI driven theatre product inventory |
| 71 | Automatic soap/alcohol gel dispensers for handwashing |
| 72 | Audit/QA of gas leaks from source to patient |
| 73 | Forum for local discussion of sustainability ideas |
| 74 | Multi-specialty operating theatres |
| 75 | Ventilation with heat rescue functionality |
| 76 | Intelligent use of operating theatre capacity to ensure maximal patient throughput |
| 77 | Reducing use of in-theatre catheterisation |
| 78 | Reuse calf compression devices (VTE prophylaxis) |
| 79 | Remove disposal cups/plates/cutlery from theatre coffee rooms |
| 80 | Reducing packaging for gowns |
| 81 | Resterilisation of single use equipment |
| 82 | Use of HEPA filters |
| 83 | Having a translucent rooftop that allows in light |
| 84 | Reducing use of plastic PPE |
| 85 | Reducing hand washing when not required |
| 86 | Recycling metal (e.g. metallic intubation blades) |
| 87 | Reduce mesh use |
| 88 | Hospital should have incinerator |

**Table S6.** Global consultation with healthcare professionals (Phase 1)

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Overall** | **HIC** | **LMIC** |
| **Sustainability leads in place** |
| None | 61.4% | 62.7% | 59.3% |
| Hospital lead only | 23.8% | 24.5% | 22.8% |
| Theatre lead only | 11.6% | 10.0% | 14.1% |
| Both Hospital + Theatre leads | 3.2% | 2.8% | 3.8% |
| **Hospital net zero target** |
| Yes | 15.6% | 15.6% | 15.7% |
| No | 84.4% | 84.4% | 84.3% |
| **Written green surgery plan** |
| Yes | 15.5% | 14.4% | 17.0% |
| No | 84.5% | 85.6% | 83.0% |
| **I care about the environmental impact of the OR** |
| Agree | 95.0% | 95.6% | 93.9% |
| Disagree | 5.0% | 4.4% | 6.1% |
| **I am willing to change my practice in the OR to reduce its environmental impact** |
| Agree | 96.5% | 97.6% | 94.6% |
| Disagree | 3.5% | 2.4% | 5.4% |
| **I have enough information about the environmental impact of the OR to inform my decisions** |
| Agree | 44.7% | 32.7% | 66.7% |
| Disagree | 55.3% | 67.3% | 33.3% |

**Table S7.** Patient perceptions of reducing the carbon and environmental impact of surgery (UK only)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Statement** | **Agreement** | **Patient (previous surgery)** | **Patient (awaiting surgery)** | **Public** | **Total** |
| I care both about the carbon footprint of my operation and my care around the time of surgery | Strongly agree | 28 (44.4) | 1 (33.3) | 5 (55.6) | 34 (45.3) |
| Agree | 25 (39.7) | 1 (33.3) | 4 (44.4) | 30 (40.0) |
| Neutral | 4 (6.3) | 1 (33.3) | 0 (0.0) | 5 (6.7) |
| Disagree | 1 (1.6) | 0 (0.0) | 0 (0.0) | 1 (1.3) |
| Strongly disagree | 5 (7.9) | 0 (0.0) | 0 (0.0) | 5 (6.7) |
| Reducing the carbon footprint of operating theatres is important to my community, family & friends | Strongly agree | 18 (28.6) | 1 (33.3) | 4 (44.4) | 23 (30.7) |
| Agree | 33 (52.4) | 1 (33.3) | 5 (55.6) | 39 (52.0) |
| Neutral | 7 (11.1) | 1 (33.3) | 0 (0.0) | 8 (10.7) |
| Disagree | 1 (1.6) | 0 (0.0) | 0 (0.0) | 1 (1.3) |
| Strongly disagree | 4 (6.3) | 0 (0.0) | 0 (0.0) | 4 (5.3) |
| I would support changes to reduce the environmental impact of my operation if the safety and effectiveness of surgery was the same or better | Strongly agree | 43 (68.3) | 2 (66.7) | 8 (88.9) | 53 (70.7) |
| Agree | 16 (25.4) | 1 (33.3) | 1 (11.1) | 18 (24.0) |
| Neutral | 3 (4.8) | 0 (0.0) | 0 (0.0) | 3 (4.0) |
| Disagree | 0 (0.0) | 0 (0.0) | 0 (0.0) | 0 (0.0) |
| Strongly disagree | 1 (1.6) | 0 (0.0) | 0 (0.0) | 1 (1.3) |
| I would support changes to reduce the environmental impact of my operation if there was a slight increase in minor complications of surgery | Strongly agree | 1 (1.6) | 0 (0.0) | 2 (22.2) | 3 (4.0) |
| Agree | 15 (23.8) | 0 (0.0) | 1 (11.1) | 16 (21.3) |
| Neutral | 13 (20.6) | 1 (33.3) | 2 (22.2) | 16 (21.3) |
| Disagree | 22 (34.9) | 1 (33.3) | 4 (44.4) | 27 (36.0) |
| Strongly disagree | 12 (19.0) | 1 (33.3) | 0 (0.0) | 13 (17.3) |
| I would support changes to reduce the environmental impact of my operation even if there was an increased cost to the NHS | Strongly agree | 6 (9.5) | 1 (33.3) | 2 (22.2) | 9 (12.0) |
| Agree | 24 (38.1) | 1 (33.3) | 4 (44.4) | 29 (38.7) |
| Neutral | 13 (20.6) | 1 (33.3) | 2 (22.2) | 16 (21.3) |
| Disagree | 12 (19.0) | 0 (0.0) | 1 (11.1) | 13 (17.3) |
| Strongly disagree | 8 (12.7) | 0 (0.0) | 0 (0.0) | 8 (10.7) |
| Hospitals should publish general information about the measures they are taking to reduce the carbon footprint of surgery | Strongly agree | 27 (42.9) | 2 (66.7) | 7 (77.8) | 36 (48.0) |
| Agree | 18 (28.6) | 1 (33.3) | 1 (11.1) | 20 (26.7) |
| Neutral | 13 (20.6) | 0 (0.0) | 0 (0.0) | 13 (17.3) |
| Disagree | 2 (3.2) | 0 (0.0) | 1 (11.1) | 3 (4.0) |
| Strongly disagree | 3 (4.8) | 0 (0.0) | 0 (0.0) | 3 (4.0) |
| Patients should be told about the specific measures taken to reduce the carbon footprint of their operation during preoperative preparation | Strongly agree | 13 (20.6) | 1 (33.3) | 5 (55.6) | 19 (25.3) |
| Agree | 23 (36.5) | 0 (0.0) | 2 (22.2) | 25 (33.3) |
| Neutral | 14 (22.2) | 1 (33.3) | 0 (0.0) | 15 (20.0) |
| Disagree | 8 (12.7) | 1 (33.3) | 1 (11.1) | 10 (13.3) |
| Strongly disagree | 5 (7.9) | 0 (0.0) | 1 (11.1) | 6 (8.0) |
| Patients should be empowered make choices to reduce the carbon footprint of their operation as part of consent | Strongly agree | 16 (25.4) | 2 (66.7) | 6 (66.7) | 24 (32.0) |
| Agree | 19 (30.2) | 1 (33.3) | 1 (11.1) | 21 (28.0) |
| Neutral | 11 (17.5) | 0 (0.0) | 1 (11.1) | 12 (16.0) |
| Disagree | 8 (12.7) | 0 (0.0) | 0 (0.0) | 8 (10.7) |
| Strongly disagree | 9 (14.3) | 0 (0.0) | 1 (11.1) | 10 (13.3) |

**Supplementary Appendixes**

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