# The carbon footprint of hospital diagnostic imaging in Australia

Scott McAlister,[a]* Forbes McGain,[b] Matilde Petersen,[c] David Story,[d] Kate Charlesworth,[e] Glenn Ison,[f] and Alexandra Barratt[g]

[a]The Centre for Health Policy, The University of Melbourne, Australia, Wiser Healthcare and Faculty of Medicine and Health, The University of Sydney, Australia, and Department of Critical Care, The University of Melbourne, Grattan St, Parkville, VIC 3010, Australia
[b]Department of Critical Care, The University of Melbourne, Australia and Western Health, Melbourne, Australia
[c]Wiser Healthcare and Faculty of Medicine and Health, The University of Sydney, Australia
[d]Department of Critical Care, The University of Melbourne, Australia
[e]Northern Sydney Local Health District, Sydney, Australia
[f]Department of Cardiology, St George Hospital, Sydney, Australia
[g]Wiser Healthcare and Faculty of Medicine and Health, The University of Sydney, Australia

**The Lancet Regional Health - Western Pacific 2022;24: 100459**
Published online xxx
https://doi.org/10.1016/j.lanwpc.2022.100459

## Summary

**Background** Pathology testing and diagnostic imaging together contribute 9% of healthcare's carbon footprint. Whilst the carbon footprint of pathology testing has been undertaken, to date, the carbon footprint of the four most common imaging modalities is unclear.

**Methods** We performed a prospective life cycle assessment at two Australian university-affiliated health services of five imaging modalities: chest X-ray (CXR), mobile chest X-ray (MCXR), computerised tomography (CT), magnetic resonance imaging (MRI) and ultrasound (US). We included scanner electricity use and all consumables and associated waste, including bedding, imaging contrast, and gloves. Analysis was performed using both attributional and consequential life cycle assessment methods. The primary outcome was the greenhouse gas footprint, measured in carbon dioxide equivalent ($CO_2e$) emissions.

**Findings** Mean $CO_2e$ emissions were 17·5 kg/scan for MRI; 9·2 kg/scan for CT; 0·8 kg/scan for CXR; 0·5 kg/scan for MCXR; and 0·5 kg/scan for US. Emissions from scanners from standby energy were substantial. When expressed as emissions per additional scan (results of consequential analysis) impacts were lower: 1·1 kg/scan for MRI; 1·1 kg/scan for CT; 0·6 kg/scan for CXR; 0·1 kg/scan for MCXR; and 0·1 kg/scan for US, due to emissions from standby power being excluded.

**Interpretation** Clinicians and administrators can reduce carbon emissions from diagnostic imaging, firstly by reducing the ordering of unnecessary imaging, or by ordering low-impact imaging (X-ray and US) in place of high-impact MRI and CT when clinically appropriate to do so. Secondly, whenever possible, scanners should be turned off to reduce emissions from standby power. Thirdly, ensuring high utilisation rates for scanners both reduces the time they spend in standby, and apportions the impacts of the reduced standby power of a greater number of scans. This therefore reduces the impact on any individual scan, maximising resource efficiency.

**Funding** Healthy Urban Environments (HUE) Collaboratory of the Maridulu Budyari Gumal Sydney Partnership for Health, Education, Research and Enterprise MBG SPHERE. The National Health and Medical Research Council (NHMRC) PhD scholarship



**Keywords:** Diagnostic imaging; Carbon footprint; Life cycle assessment; Net-zero carbon; Aging; Comorbidities

## Introduction

In 2020-21, many of the world's major economies made pledges to become carbon neutral between 2050 and 2060, including interim carbon emission reduction

*Corresponding author.
*E-mail address:* scott.mcalister@unimelb.edu.au (S. McAlister).

## Research in context

*Evidence before the study*

We searched the Scopus from its inception up to Feb 22, 2021, using the terms ("life cycle assessment" OR LCA OR "greenhouse gas footprint" OR "GHG footprint" or "carbon footprint") AND ("computerised tomography" OR "magnetic resonance imaging" OR ultrasound OR x-ray). Only two studies using life cycle assessment to determine the carbon footprint of diagnostic imaging were found. The first used both estimated examination times and power usage to calculate the carbon footprint of ultrasound, computerised tomography and magnetic resonance imaging rather than undertaking actual measurements, meaning the results are not accurate. The second was an attributional life cycle assessment that determined the carbon footprint of magnetic resonance imaging was 22.4 kg carbon dioxide equivalents.

*Added value of the study*

This is the first study to calculate the carbon footprint using life cycle assessment of the five most common imaging modalities. Additionally, it is the first study to perform both attributional and consequential life cycle assessment of diagnostic imaging.

*Implications of all the available evidence*

The study identifies three main ways that clinicians and administrators can reduce the carbon impacts of diagnostic imaging. (1) By reducing unnecessary imaging, or by changing imaging to a lower carbon modality; (2) By turning scanners off when they are not required rather than leaving them in standby; (3) By ensuring existing scanners have high utilisation rates.

targets by 2030.[1] Furthermore, in August 2021 the Intergovernmental Panel on Climate Change (IPCC) released the first part of its Sixth Assessment, which states emphatically that globally we need to achieve net-zero carbon emissions as quickly as possible to stabilise global warming.[2] Decarbonising the economy to achieve net-zero emissions necessarily includes healthcare. Globally, healthcare is responsible for 4·4% of annual greenhouse gas emissions,[3] with emissions from individual countries such as UK, Australia and the US being higher than the global average (5%, 7% and 10% respectively).[4–6] According to the UK's National Health Service (NHS), buildings currently only contribute approximately 12% to the NHS's total carbon footprint, with approximately 50% arising from pharmaceuticals and procurement.[4] Assuming other health services are similar, rather than focusing on buildings, which will see mitigation occurring naturally from market-based mechanisms as energy systems move from fossil fuels to renewable energy, a larger reduction in healthcare's carbon footprint will be achieved by changes to clinical care.[7]

A recent Australian study by Malik et al investigating the carbon footprint caused by the whole health system of the state of New South Wales found that pathology and diagnostic imaging together accounted for approximately 9% of this healthcare footprint,[8] with the demand for imaging services per 100 people in Australia increasing by 9% over a five-year period.[9] The carbon impacts of pathology testing have been reported,[10,11] but to date there has not been a detailed analysis of the carbon impacts of the most commonly used diagnostic imaging modalities using a standard methodology. Yet imaging is ubiquitous in healthcare globally. High rates of overuse and inappropriate use for screening and diagnosis have been demonstrated, including in low and middle-income countries,[12] despite underuse and lack of access remaining problems in low-income settings.[13]

To support the more appropriate use of imaging, practitioners and policymakers need comparative data on different, commonly used imaging modalities, including data on the carbon emissions associated with their use. In this study, therefore, we aimed to estimate the carbon footprint of five common imaging modalities within an Australian public hospital setting: computerised tomography (CT); magnetic resonance imaging (MRI); ultrasound (US); chest X-ray (CXR); and mobile CXR (MCXR) in a "cradle to grave" life cycle assessment. Life cycle assessment (LCA) is a method for estimating the environmental impacts of products and services over their whole life cycle (raw material extraction, material processing, manufacture, use and end-of-life).[14]

## Methods

### Overview of methods

We used process-based LCA to undertake both attributional (ALCA) and consequential (CLCA) analyses, in accordance with the International Organization for Standardization (ISO) standard 14040:2000.[14] Attributional and consequential LCA methods provide complementary perspectives of the carbon impacts of imaging.

In the case of imaging, ALCAs determine what share of the total impact from operating a given modality can be attributed to a single scan (mean impact), helping to identify the sources and magnitude of operating diagnostic imaging as a whole. By contrast, CLCAs only model the changes, such as a scanner moving from standby to active, that result from undertaking one additional (or fewer) scans within an already operational system (Box 1).[15]

### Study setting

We assessed the carbon footprint of four imaging modalities (CT, US, CXR, MCXR) at St George Hospital, a 653-bed tertiary referral hospital in metropolitan Sydney, Attributional impact is given by:

$W_{ALCA} = W_O + (W_S.T_S)/T_O$

where $W_{ALCA}$ is total attributional impact measured in Watts, $W_O$ is Watts consumed when operating, $W_S$ is Watts consumed in standby, $T_S$ is total standby time and $T_O$ is total operational time.

In an example where the operational power consumption of a scanner is 500W per hour, standby power is 100W per hour, and the scanner is only operational for 2 h per day, with it being in standby the rest of the time, the attributional impact per hour of operation is:

1,600 W = 500 + (100×22)/2

In a consequential analysis, the proportion of standby energy is not included, as the scanner is sitting in standby regardless of whether it is used or not. The consequence of using the scanner, therefore, is only the difference between standby and operational power, and hence the consequential impact per hour of operation is 400W (500W − 100W).

***Box 1*: Difference between attributional and consequential LCA.**

Australia. Chest X-rays were chosen as they were the most commonly performed X-ray during the study period (338 CXRs compared to 261 combined for all other body imaging). The mobile X-ray scanner was located in the intensive care unit. Approval for this project was obtained from the South Eastern Sydney Local Health District (SESLHD) Human Research Ethics Committee: 2020/ETH03343. An error occurred from the power logger during the data collection of the MRI scanner at St George Hospital. A COVID-19 outbreak in Sydney prohibited further access to St George to repeat the data collection. The carbon footprint of MRI imaging, therefore, was undertaken at Footscray Hospital in Melbourne, Australia a 290-bed acute teaching hospital; ethics approval was waived by the Western Health Ethics Committee.

## Study design

The functional unit of the ALCA is a CT, MRI, US, CXR or MCXR, in an Australian public hospital setting, while the functional unit of the CLCA is an additional CT, MRI, US, CXR or MCXR, in an Australian public hospital setting. The system boundary, defining what is included and excluded by the study, is shown in Figure 1. Capital infrastructure, including the manufacture of scanners, was excluded as environmental impacts are amortised over long periods of time and are typically small.

We additionally chose to exclude the energy used by both the hospital's HVAC (heating, ventilation, and air conditioning) system and the room-specific air conditioning energy required to maintain the CT and MRI scanner rooms at 18°C, so as to make the results generalisable irrespective of geographic location and time of year. This was based on our previous study in which we calculated the HVAC energy requirements for a hospital ward in two different geographic and climatic locales, with the study showing that HVAC energy varied greatly due to both location and time of year.[16] Furthermore, any additional cooling over and above what is provided by the hospital's HVAC system is similarly dependent on the set temperature of the hospital's HVAC system (a lower set temperature requires less additional cooling), making it difficult to properly attribute impacts for cooling between the hospital's HVAC and any additional cooling.

## Study outcomes

The primary outcome was carbon emissions in kilogram carbon dioxide equivalents (kg $CO_2e$).

## Data collection

All data were collected between 10 February 2021 and 30 August 2021. The electrical power consumed by each modality was collected, as was the weight and composition of materials used by patients and staff such as sheets, gloves, gowns, contrast, needles and syringes (consumables) (appendix pg 1). These materials were weighed with a Satrue KA-1000 scale (resolution 0·5g). Usage of consumables was estimated by the radiographers undertaking the scans and X-rays. Three-phase electrical power (400 volts) was measured sequentially during the collection period for each of the CXR, CT and MRI imagers (1·5 Tor) for a period of approximately two weeks by a Hioki PW3365-20 power meter (Hioki, Nagano Japan), using a sampling rate of one sample every 15 s. Single phase electrical power (230 volts) measured by a Watts Up Pro power meter (Vernier, Oregon USA) connected to Logger Pro 3·14·1·0 (Vernier) with a sample obtained every 30 s for a period of two weeks for US, and for four days for MCXR. Power consumption of computers and monitors in the imaging control rooms was obtained from manufacturers' published data.

## Data analysis

To calculate power usage for CT, MRI, US and CXR, power usage was divided into two states: active power (including positioning a patient or scanner, and imaging the patient), and standby power for all other times. Additionally, two distinct standby power states were identified for CT, MRI and US imaging devices; passive standby, when the scanner was in a deep low-power mode overnight, and active standby, for the time the imager was in-between patients during operational hours (appendix pg 3).

For the ALCA, the average power consumed by each modality was estimated as the sum of the average active power (per minute for US, CT, and MRI, or per image for CXR) added to its respective proportion of standby power on a per minute basis, including computers and monitors. For the CLCA, power usage of scanners was estimated as being the difference between the average active power and active standby power per minute. The impacts of computers and monitors were not included in the CLCA analysis, as these were running regardless of an image being ordered.

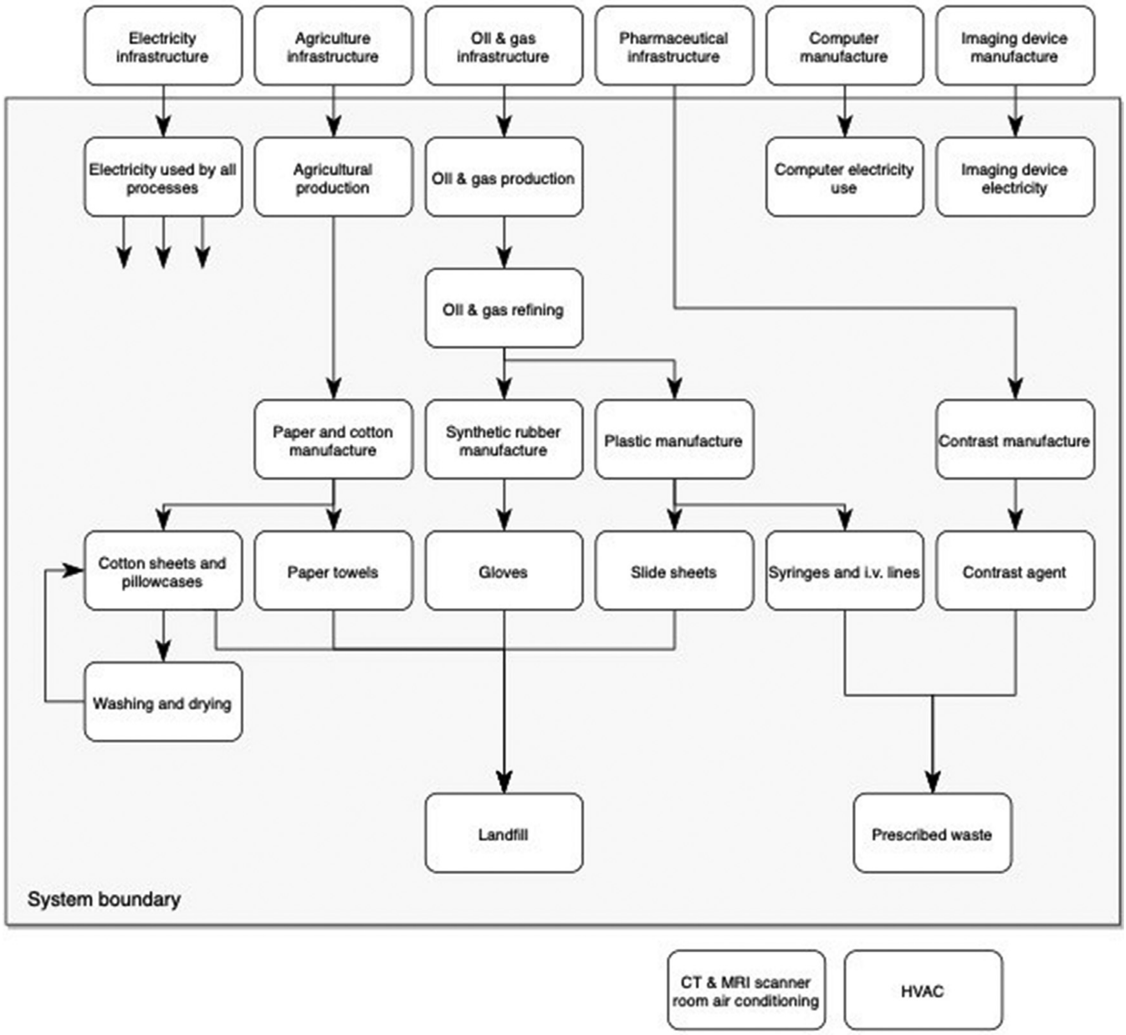


**Figure 1.** System boundary of study inclusions and exclusions.

As the MCXR operates on battery power, two charging modes were identified: active charging, when the mobile unit was first plugged back into the charger after performing imaging, and trickle charging when the unit's battery was fully charged. For the ALCA, power usage per MCXR was estimated as the sum of the total power divided by the total number of MCXRs performed. For the CLCA, power usage was estimated as the difference per minute in active and passive charging, multiplied by the time per MCXR, calculated as being the total time unplugged from the charger divided by the total number of MCXRs.

Carbon emissions from all parts of the life cycle were modelled using SimaPro 9·0·0·27 (PRé Sustainability, Amersfoot the Netherlands). Background data on the environmental impacts of materials and energy used, such as plastics and electricity, was obtained from the attributional and consequential versions of the ecoinvent 3·5 database (ecoinvent, Zurich Switzerland).[17] Australian electricity generation mixes and emission factors are available in appendix pg 4. The impact assessment was modelled using the ReCiPe 2016 (H) impact assessment model.[18] Details of the LCA processes and data sources, including conversion factors, are provided in supplementary material pg 8.

### Role of the funding sources

The funding sources played no role in the study design, data collection, data analysis, interpretation, or the writing of the manuscript.

## Results

All imaging devices spent considerably more time in standby mode compared to active mode (Table 1),

| | Total time spent - hrs | Total scans | Average scans per week | Average time (min) per scan (95% CI) | Total power kWh | Average power Wh/min | ALCA power Wh/min | CLCA power Wh/min |
|---|---|---|---|---|---|---|---|---|
| CT Active | 28·2 | 399 | 200 | 8·4±0·2 | 278 | 164 | 939 | 64 |
| CT Active standby | 145·6 | | | | 927·5 | 106 | | |
| CT Passive standby | 162 | | | | 280·7 | 29 | | |
| MRI Active | 110·5 | 245 | 122 | 26·7±2.5 | 1749.3 | 265 | 605 | 91 |
| MRI Active standby | 63·4 | | | | 660.1 | 174 | | |
| MRI passive standby | 163·1 | | | | 1473·6 | 151 | | |
| US Active | 48·4 | 146 | 69 | 19·9±2.1 | 25·5 | 9 | 23 | 0.85 |
| US Active standby | 69·2 | | | | 33·4 | 8 | | |
| US passive standby | 237·6 | | | | 5·2 | 0.4 | | |
| | **Total time spent - hrs** | **Total scans** | | **Average time (min) per CXR (95% CI)** | **Total power - kWh** | **Average power Wh/CXR** | **ALCA power Wh/ CXR** | **CLCA power Wh/ CXR** |
| CXR Active | 1·2 | 47 | 24 | 1·5±0·3 | 0·7 | 10 | 171 | 5 |
| Total X-ray Standby | 321·3 | | | | 114 | 6 | | |

***Table 1*: Electrical power consumed, and time spent in each operating mode, with calculated attributional (ALCA) and consequential (CLCA) power use.**

ranging from 67% time in standby for MRI through to 99·6% for X-ray. Mean examination time was longest for MRI imaging at almost 27 min, followed by US (20 min), CT (8·4 min) and CXR (1·5 min). MCXR's time per scan was 6·9 min, as this included all the time the scanner was being moved between patients. So as to focus primarily on the four most common modalities, further results for the MCXR can be found in the appendix (pg 5).

ALCA power consumption was higher than both mean power consumption (total power divided by total time in a given mode) and CLCA power consumption due to the high proportion of time spent in standby for all modalities (Table 1). Whilst an MRI scanner has the highest mean power consumption per minute of operation in all modes (active and standby) of all the imaging modalities due to its superconducting magnets needing to be constantly cooled to approximately -270°C by liquid nitrogen, it had a lower attributional power consumption compared to the CT scanner. This difference was due to the CT scanner being in standby mode for considerably longer than the MRI scanner (92% of total time vs. 67%), resulting in each active minute of the CT scanner having a greater number of standby minutes attributed to it.

For carbon emissions, focusing firstly on ALCA, MRI and CT had the highest emissions of the imaging modalities at 17·5 and 9·2 kg $CO_2$e per scan respectively (Table 2), with the majority of this impact (MRI - 94%, CT - 91%) resulting from electricity use (Figure 2). For MRI, the impact of consumables came predominantly from the cotton drawsheets (0·7kg $CO_2$e, or 4% of total impact), whilst for the CT it originated primarily from the contrast tubing, the cotton sheet and pillowcase (both 0·4 kg $CO_2$e, 4%) and the contrast tubing (0·3 kg $CO_2$e, 3%)(appendix p6). US and CXR had similar carbon impacts (0·76 and 0·53 kg $CO_2$e respectively). Notably, whilst the dominant source of emissions for US (as for MRI and CT) is electricity (87%), the major source of impacts for the CXR is the washing and drying of the cotton sheet and pillowcase (0·67 kg $CO_2$e, 88%), with electricity only contributing 0·02 kg $CO_2$e, or 3% of the total impact.

| | Attributional LCA per scan (mean) | | | | Consequential LCA per additional scan | | | |
|---|---|---|---|---|---|---|---|---|
| | Total $CO_2$e/No. of tests ordered (i.e. average) | | | | Additional $CO_2$e used for one more scan | | | |
| | **MRI** | **CT** | **CXR** | **US** | **MRI** | **CT** | **CXR** | **US** |
| Average scan time | 27 min | 8 min | 2 min | 20 min | 27 min | 8 min | 2 min | 20 min |
| Consumables | 1·0 | 1·1 | 0·74 | 0·07 | 0·8 | 1·02 | 0·58 | 0·084 |
| Electricity | 16·5 | 8·1 | 0·02 | 0·46 | 0·3 | 0·07 | 0·002 | 0·002 |
| Total | 17·5 | 9·2 | 0·76 | 0·53 | 1·1 | 1·09 | 0·58 | 0·09 |

***Table 2*: Carbon emissions for each imaging modality, kg $CO_2$e/scan.**

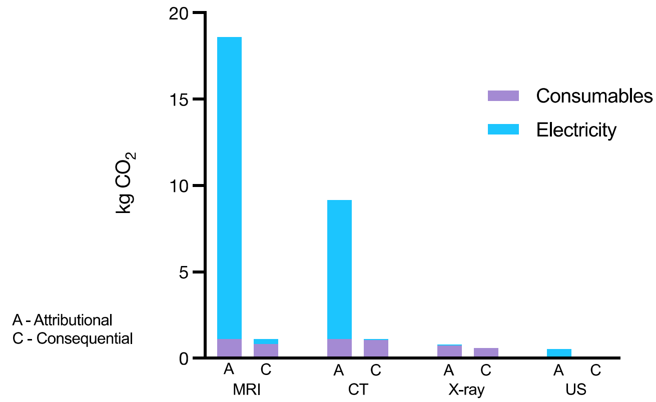


**Figure 2.** Carbon emissions from electricity and consumables (in kg $CO_2e$) of imaging modalities, as estimated by ALCA and CLCA.

Carbon emissions for MRI, CT and US were 84% to 94% lower in CLCA compared to ALCA, due to the exclusion of standby power in the calculated impact. MRI and CT remained the imaging modalities with the largest impacts (1·1 and 1·09 kg $CO_2e$ respectively). For CXR, the impact fell only slightly from 0·8 to 0·6 kg $CO_2e$ compared to ALCA, as the main source of impact that originated from sheet and pillowcase laundering remained the same

## Discussion

### Statement of principal findings

We report for the first time the life cycle carbon footprint of all major diagnostic imaging modalities. Magnetic resonance imaging (MRI) and computerised tomography (CT) have large carbon footprints compared to the "traditional" imaging modalities of X-rays and ultrasound. This finding was observed when emissions were calculated per scan (ALCA) and when calculated per additional scan (CLCA), but was most marked using the attributional approach (ALCA), with high emissions per scan for MRI and CT (MRI – 17·5 kg $CO_2e$, CT – 9·2 kg $CO_2e$,) compared to chest X-ray and ultrasound (0·76 and 0·53 kg $CO_2e$ respectively). As a comparison, a MRI scan has equivalent carbon emissions to driving a new European car 145km, a CT scan 76 km, a chest X-ray 6 km, and a US scan 4 km.[19] The majority of MRI's and CT's large carbon footprints are due to electricity use, and in particular, their standby power use.[17]

Emissions calculated per additional scan (CLCA approach) were smaller in absolute magnitude, particularly for MRI and CT, due to the effect of excluding standby power, but the same pattern remained.

### Strengths and limitations

A key strength of our study is that we used process-based LCA to measure carbon emissions released by all energy and materials consumed in the process of imaging, as defined by our system boundary. Process-based LCA provides an accurate estimate of emissions at the level of individual healthcare activities, in this case imaging modalities, which allows for these activities to be compared, and for targeted mitigation strategies to be developed. As such, our study cannot be directly compared to LCA studies which estimate carbon emissions of the healthcare sector, or parts of it, by using economic models (Environmental Input-Output LCA).

A further strength is that our study calculated emissions per scan and per additional scan (using ACLC and CLCA approaches, respectively). The benefit of providing both measures is the insights afforded by these complementary data. ALCA provides information on the current contribution from each type of imaging to healthcare's carbon footprint, whilst CLCA estimates the actual change in emissions that will occur from either ordering one more or one less additional scan.

Our study has limitations. We excluded the environmental impact of the manufacture of radiological equipment due to the amortised impact per scan being known to be very small,[20] and because it cannot be estimated with precision without detailed manufacturer's data about the weights and composition of all of a scanner's components (generally not available for commercial in confidence reasons). Nonetheless, to explore this issue we used publicly available data (appendix pg 7) together with the usual duration of a machine life of 10–15 years to estimate this impact. We estimate an impact of manufacturing in the range 0.00007 to 0.043 kg $CO_2e$ per scan, resulting in no important changes to our results. Another limitation is that we only investigated a single scanner of each modality in a public hospital setting in one country. Large differences in scanner energy consumption have been reported, due to both differences in actual scanners as well as usage patterns.[21,22] Because of this variability, absolute levels of emissions at other sites may differ. Our study, however, does show their expected relative magnitude. We therefore recommend that further studies be undertaken to measure a range of scanners of varying ages, sizes, and manufacturers, as well as in different settings (e.g. private radiology, general hospital, or emergency department).[22] Lastly, we did not include the cooling energy required to keep CT and MRI scanners in a cool ambient temperature room as it is heavily dependent on external temperature and humidity, and difficult to separate from the overall building energy demand of the hospital. The effect of this omission, however, is only to underestimate the total environmental impact of these imaging modalities.

### Findings in context

There have been only a few dozen process-based LCA studies of specific healthcare items or activities in the world. Only one study calculated the carbon impact of common imaging modalities, finding that the attributional carbon footprint of an MRI was 22.4 kg $CO_2$e, similar to our 17.9 kg $CO_2$e.[22] There are other studies that have focussed primarily on the power consumption of scanners, with our study's results on consumption falling broadly in line in comparison to these other studies.[23]

Of note, our results should draw attention to the carbon impacts of imaging in comparison to other carbon hotspots which have received much attention. For example, anaesthesia is a recognised carbon hotspot,[23] yet one MRI has approximately equivalent emissions to one gaseous general anaesthetic.[24] Thus far, however, the carbon emissions from imaging have received little attention.

### Implications for policy and practice

There are three main opportunities to reduce the carbon emissions associated with diagnostic imaging. Firstly, imaging is currently often overutilised in clinical care. As an example, a review investigating the overuse of testing in Australia found studies showing 34–62% of computed tomography scans of pulmonary arteries in suspected pulmonary thromboembolism, 36–40% of imaging tests in patients with low back pain, and 54% of imaging tests in patients with abdominal pain were unnecessary.[25] There are therefore likely opportunities for clinicians to reduce their use of low-value scans, or to substitute high-carbon modalities for low ones, such as using US in place of MRI when it is clinically appropriate to do so. For example, US is clinically preferred over MRI for shoulder impingement/rotator cuff symptoms,[26] and echocardiography has advantages over cardiac MRI when investigating asymptomatic patients in the context of inherited heart conditions.[27] Clinicians may identify further opportunities to evaluate whether less intensive imaging may provide better health outcomes with less environmental impact, with further research measuring health outcomes, costs and environmental impacts of low carbon clinical care options being urgently needed to give clinicians confidence to change their practice when it is clinically appropriate to do so.

Secondly, for all imaging modalities, the difference between ALCA and CLCA reveals the large impacts of standby energy use, when a machine is on but not being utilised, with this also noted by other authors.[28] Especially for hospitals where machines are required to be on 24/7 for emergency use, this standby energy use represents the unavoidable impact of operating a machine. Impacts can, however, be decreased by reducing the number of machines that are on to match demand, hence increasing the utilisation rates of the operating machines. As an example, if the CT scanner in our study spent the same amount of time being utilised as the MRI scanner (8% vs. 33% active scanning time), then its attributional power use would fall from 939 to 237 Wh/min. Overall, further reductions could be seen if scanners were turned off at times of low demand when less elective healthcare is being performed, such as overnight, at weekends or on holidays, especially if there are duplicates of equipment allowing one to be on for emergency use. Whilst MRI scanners cannot be turned off as the magnet needs to be constantly cooled, this is possible for all other scanners.

Thirdly, manufacturers could seek to reduce the power used by scanners in different standby modes, and similarly, hospital administrators could include standby power usage as a decision criterion when seeking to purchase new equipment.

Lastly, given the unavoidable environmental cost of operating particularly MRI and CT scanners, it would be preferable to ensure high utilisation rates of existing scanners in a locale before ordering additional scanners. As an example, in 2019 Australia was second only to Japan in the number of CT scanners per capita (70 scanners per million population), an 85% increase since 2015. The utilisation rate of each of these scanners is 2,020 scans per year, approximately one third of the USA's 6,199 scans per year, suggesting there is an opportunity for greater utilisation, and hence a reduced environmental impact.[29]

As the primary carbon impact for imaging results from electricity use, it could be considered that the increases seen in low carbon renewable energy entering electricity grids mean that better utilisation of scanners and reduced ordering of imaging does not need to occur. There are, however, currently few countries or states that have 100% renewable energy, with renewable energy making up only 28% of global electricity generation.[30]

Given the need for rapid decarbonisation, reducing the carbon impact from imaging will require input from clinicians to both only order imaging when necessary, and where possible to order X-rays or ultrasound in preference to MRI or CT imaging; from administrators in choosing when to purchase new scanners, and to choose scanners that have low standby power usage; and that non-MRI scanners are turned off wherever possible out-of-hours.

## Contributors

Scott McAlister - Project administration, Methodology, Investigation, Formal analysis, Writing - original draft

Alexandra Barratt - Critical review and revision of manuscript, assistance with project management

Forbes McGain - assistance in developing the methods, project management assistance, critical review and revision of the manuscript.

David Story - assistance with project management, resources, critical review and revision of the manuscript

Matilde Breth-Petersen - data collection, critical review and revision of the manuscript.

Kate Charlesworth - assistance with study idea, assistance with project, revision of manuscript

Glenn Ison - data collection, critical review and revision of the manuscript.

## Data sharing statement

Raw data from the power loggers will be available after approval of a proposal from scott.mcalister@unimelb.edu.au, until 31/12/23.

## Declaration of interests

Scott McAlister was funded by a National Health and Medical Research Council of Australia (NHMRC) PhD scholarship, and from the Healthy Urban Environments (HUE) Collaboratory of the Maridulu Budyari Gumal Sydney Partnership for Health, Education, Research and Enterprise MBG SPHERE.

Alexandra Barrett is funded by a National Health and Medical Research Council of Australia (NHMRC) Centre of Research Excellence Grant, No 1004136.

Kate Charlesworth was funded from the Healthy Urban Environments (HUE) Collaboratory of the Maridulu Budyari Gumal Sydney Partnership for Health, Education, Research and Enterprise MBG SPHERE.

## Acknowledgements

We would like to thank the radiology and engineering staff at both St George and Footscray Hospitals, for all their help in facilitating the data collection for this research. We would like to especially thank Lauren McGuire and Louise Mackie from Footscray Hospital, for their assistance in answering questions during all the stages of the project.

## Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.lanwpc.2022.100459.

## References

1 The United States Briefing Room The Whitehouse. Leaders summit on climate summary of proceedings. 2021; published online April 23. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/23/leaders-summit-on-climate-summary-of-proceedings/. Accessed 1 June 2021.
2 IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2021. In Press.
3 Lenzen M, Malik A, Li M, et al. The environmental footprint of health care: a global assessment. *Lancet Planet Health*. 2020;4:e271–e279.
4 Tennison I, Roschnik S, Ashby B, et al. Health care's response to climate change: a carbon footprint assessment of the NHS in England. *Lancet Planet Health*. 2021;5:e84–e92.
5 Malik A, Lenzen M, McAlister S, McGain F. The carbon footprint of Australian health care. *Lancet Planet Health*. 2018;2:27–35.
6 Eckelman MJ, Sherman J. Environmental impacts of the U.S. health care system and effects on public health. *PLoS One*. 2016;11:e0157014.
7 Sherman JD, McGain F, Lem M, Mortimer F, Jonas WB, MacNeill AJ. Net zero healthcare: a call for clinician action. *BMJ*. 2021;374:n1323.
8 Malik A, Padget M, Carter S, et al. Environmental impacts of Australia's largest health system. *Resour Conserv Recycl*. 2021;169:105556.
9 Australian Institute of Health and Welfare. Specialist, pathology and other diagnostic services. 2021; published online Jan 6. https://www.aihw.gov.au/reports/australias-health/specialist-pathology-and-other-diagnostic-services. Accessed 22 Feb 2022.
10 McAlister S, Grant T, McGain F. An LCA of hospital pathology testing. *Int J Life Cycle Assess*. 2021;26:1753–1763.
11 McAlister S, Barratt AL, Bell KJ, McGain F. The carbon footprint of pathology testing. *Med J Aust*. 2020;212:377–382.
12 Brownlee S, Chalkidou K, Doust J, et al. Evidence for overuse of medical services around the world. *Lancet*. 2017;390:156–168.
13 Glasziou P, Straus S, Brownlee S, et al. Evidence for underuse of effective medical services around the world. *Lancet*. 2017;390:169–177.
14 The International Organization for Standardization. ISO 14040:2006 Life cycle assessment - Principles and framework. 2006. https://www.iso.org/standard/37456.html.
15 Weidema B. Market information in life cycle assessment, Environmental Project No. 863 2003. Copenhagen, Denmark: Danish Environmental Protection Agency; 2003. https://lca-center.dk/wp-content/uploads/2015/08/Market-information-in-life-cycle-assessment.pdf.
16 McGain F, Burnham JP, Lau R, Aye L, Kollef MH, McAlister S. The carbon footprint of treating patients with septic shock in the intensive care unit. *Crit Care Resusc*. 2018;20:304–312.
17 Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess*. 2016;21:1218–1230.
18 Huijbregts MAJ, Steinmann ZJN, Elshout PMF, et al. ReCiPe 2016 v1.1 A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization RIVM : Report 2016-0104a. BA Bilthoven, The Netherlands: National Institute for Public Health and the Environment; 2017. https://www.pre-sustainability.com/download/Report_ReCiPe_2017.pdf.
19 National Transport Commission. Carbon dioxide emissions intensity for New Australian light vehicles 2019. 2020 https://www.ntc.gov.au/sites/default/files/assets/files/Carbon-dioxide-emissions-intensity-for-new-Australian-light-vehicles-2019.pdf.
20 Marwick TH, Buonocore J. Environmental impact of cardiac imaging tests for the diagnosis of coronary artery disease. *Heart*. 2011;97:1128.

21 Sheppy M, Pless S, Kung F. *Healthcare Energy End-Use Monitoring*. Colorado, USA: U.S Department of Energy National Renewable Energy Lab; 2014. https://www.nrel.gov/docs/fy14osti/61064.pdf.
22 Heye T, Knoerl R, Wehrle T, et al. The energy consumption of radiology: energy- and cost-saving opportunities for CT and MRI operation. *Radiology*. 2020;295: 192084.
23 Whiting A, Tennison I, Roschnik S, Collins M. Surgery and the NHS carbon footprint. *Bull R Coll Surg Engl*. 2020;102:182–185.
24 McGain F, Sheridan N, Wickramarachchi K, Yates S, Chan B, McAlister S. Carbon footprint of general, regional, and combined anesthesia for total knee replacements. *Anesthesiology*. 2021. https://doi.org/10.1097/ALN.0000000000003967. published online Sept 16.
25 Scott IA. Audit-based measures of overuse of medical care in Australian hospital practice. *Intern Med J*. 2019;49:893–904.
26 Lenza M, Buchbinder R, Takwoingi Y, Johnston RV, Hanchard NC, Faloppa F. Magnetic resonance imaging, magnetic resonance arthrography and ultrasonography for assessing rotator cuff tears in people with shoulder pain for whom surgery is being considered. *Cochrane Database Syst Rev*. 2013;9:CD009020. https://doi.org/10.1002/14651858.CD009020.pub2.
27 Ross SB, Jones K, Blanch B, et al. A systematic review and meta-analysis of the prevalence of left ventricular non-compaction in adults. *Eur Heart J*. 2019;41:1428–1436.
28 Esmaeili A, Twomey JM, Overcash MR, Soltani SA, McGuire C, Ali K. Scope for energy improvement for hospital imaging services in the USA. *J Health Serv Res Policy*. 2015;20:67–73.
29 OECD: Organisation for Economic Co-operation and Development. Health care resources: medical technology. 2019; published online Dec 31. https://stats.oecd.org/index.aspx?queryid=30184. Accessed 2 June 2021.
30 IEA. Global energy review 2020. France, 2020 https://iea.blob.core.windows.net/assets/7e802f6a-0b30-4714-abb1-46f21a7a9530/Global_Energy_Review_2020.pdf.