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The environmental effects of non-invasive cardiac imaging

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ABSTRACT

The healthcare sector is a major contributor to the universal climate footprint, of this a significant proportion is attributable to medical imaging and further to dedicated cardiac imaging. The increasing availability and utility of cardiac imaging techniques for prognosis, diagnosis and management raises concerns for the impact of these investigations on the environment.

Our objective was to review the published literature assessing the environmental impact of non-invasive imaging modalities within cardiology, subsequently helping guide physicians toward a more sustainable approach to cardiac imaging and improved awareness of the environmental impact of healthcare within this field.

We conducted a systematic review of studies measuring the environmental impact of non-invasive cardiac imaging. A total of 8 studies were included in the final analysis.

Cardiac imaging has a significant environmental impact, which varies by modality: lowest for echocardiography and highest for MRI. As a whole this field represents a significant contributor to climate-related threats to human health, which we should strive toward harm minimisation. This may be mitigated through the conscious utilisation of energy consumption and contrast media, as well as healthcare worker education and quality improvement to guide imaging choice based on environmental impact alongside conventional determinants such as patient characteristics, clinical guidelines and cost (visual abstract).

1. Introduction

The global healthcare sector is a major contributor to greenhouse gas emissions and is responsible for around 5 % of CO_2 emissions [1] although has been reported as high as 10 % in industrialized nations [2]. Radiology and medical imaging departments contribute up to 1 % of total global emissions [3]. Cardiovascular exams represent a large proportion of medical imaging acquired worldwide annually [4] and therefore there is increasing significance placed on the cardiac imaging community to ensure we deliver sustainable best practice care.

Despite the burden of cardiovascular disease worldwide and the predicted increase in demand for cardiac imaging there is a paucity of data assessing the environmental footprint/effects of guideline directed cardiac imaging. Additionally, current evidence based guidelines from major international cardiology groups, such as the European Society of Cardiology (ESC) or the American Heart Association, do not incorporate the environmental impacts of cardiac imaging, such as using an internationally recognised assessment like the Life Cycle Assessment (LCA). A LCA is defined as the systematic analysis of the potential environmental impacts of products or services during their entire life cycle [5].

The aim of this study was to assess the environmental footprint of non-invasive cardiac imaging (focusing on echocardiography, cardiac computed tomography and cardiovascular magnetic resonance imaging), identify potential modifiable factors, and highlight potential strategies to help healthcare sustainability, as well as future needs in this space.

2. Methods

A systematic review of the literature was conducted using search terms “cardiology”, “medical imaging”, “carbon dioxide emissions”, “environmental”, “carbon” and “climate”. These were combined with MESH terms “adult” and keys words “cardiac”. Databases searched included Embase and Pubmed with applied limits of English Language and year of publication 2000 to current. The systematic review was performed according to guidelines of the Preferred Reporting Items for

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Systematic Reviews and Meta-Analyses (PRISMA) statement. Fig. 1 shows the selection process.

Inclusion criteria included 1) all study types, 2) published since the year 2000, 3) in English, 4) assessment of the environmental impact of 5) non-invasive cardiac imaging modalities (CT, MRI, echocardiography, nuclear medicine). 44 articles were initially identified and exported to Covidence, then duplicates removed. There were then 36 abstracts and these were assessed for eligibility (by KG, RK). 26 abstracts were excluded because they did not meet the pre-defined inclusion criteria. The full text publications of the remaining 10 articles were assessed (by KG, RK) for eligibility, and a further 2 were excluded, which left 8 publications to be included in the final analysis.

Data was extracted and analysed by two independent reviewers (KG, RK). For each identified study the publication details, study characteristics, outcomes and observations were summarised (Table 1). Discrepancies were resolved through discussion and consensus. Due to the diversity of study type and assessment method, quantitative analysis or pooling of the data was not conducted. Fig. 1 shows a flow diagram of the methodology process.

3. Results

A total of 36 articles were identified and screened for suitability. Of these articles, 8 articles met the inclusion and exclusion criteria and were included in the final analysis. Table 1 details all the publication study characteristics and findings. These included a variety of study types including systematic reviews (4), a literature review (1), an original research article (1), and educational reviews (2). Given the heterogeneity of studies included for analysis, meta-analysis was unable to be performed.

All studies aimed to identify the environmental footprint of medical imaging. Five of the identified studies (62.5 %) related specifically to cardiac imaging, including echocardiography, cardiovascular magnetic resonance imaging (MRI) and cardiac computed tomography (CT).

Half of the studies (4) measured CO_2 emissions as an indicator of environmental impact. Energy consumption was measured by two studies, life cycle assessment (LCA) by two studies, and disability adjusted life years (DALY) by two studies. One study measured the volume of iodinated contrast media (ICM) used and wasted, and a further study specifically measured the costs associated with MRI imaging scanners *via* a descriptive analysis.

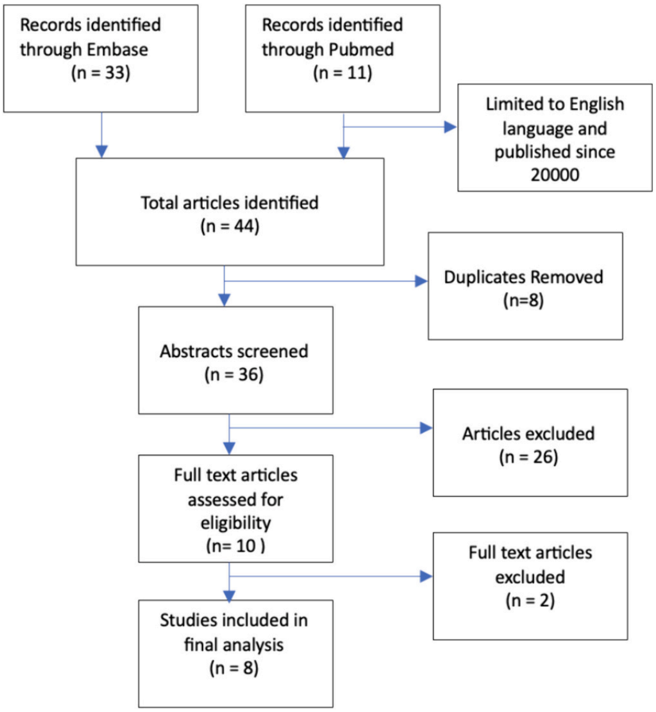

Fig. 1. Flow diagram of citation search.

The environmental impact of MRI was most commonly described, with 6 studies (75 %) assessing MRI either alone or in comparison to another imaging modality. MRI as an imaging modality was shown to have a significant environmental impact based on energy consumption, CO_2 emissions, disability adjusted life years and ecotoxicity.

A total of five studies reported on ultrasound and echocardiography-based techniques. Of these, all reported that this imaging modality is associated with lowest environmental impact compared to CT and MRI. Ultrasound was consistently shown to have ~1 to 5 % the impact of MRI regardless of measurement [4,6,7]. One study reported echocardiography energy consumption as 760kWh/year compared to 111,000kWh/year for CT and 410,000kWh/year for MRI [6] and in keeping with this, another study showed echocardiography to have lower CO_2 emissions [4]. Marwick *et al*, in a cardiac imaging dedicated study, demonstrated echocardiography to have significantly lower potentially displaced fraction of species per m^2 and ecotoxicity in comparison to MRI [7].

A literature review performed by Qin *et al* explored the possibility of low field cardiac MRI using a 1.5 T scanner in comparison to a traditional 3 T scanner [8]. Taking into consideration the helium use in cooling processes for traditional MRI machines, the use of low field scanning would enable new cryocooling techniques which use direct conduction cooling, saving up to 6000 kg of non-renewable liquid helium. It is estimated that a typical MRI scanner operates with 1500-2000 L of liquid helium and uses up to 10,000 L overs its estimated 13 year life span or estimated at 1648 kWh energy consumption per year [9].

Additionally, Chaban *et al* [9] assessed the substantial electricity demand of MRI throughout its various phases of production and usage. Production phase, incorporating raw materials through to delivery, consumes 2.73 million MJ (753,000 kWh) of fossil fuels. The use phase, incorporating installation through to decommission, estimates emissions as 20 kg CO2 equivalents *per exam*. This is equivalent to 82.5 km driven by an average gasoline powered passenger vehicle [10].

Only a single study performed by Marwick *et al* used life cycle assessment (LCA) to quantify the environmental impact of cardiac imaging [7]. LCA is an internationally recognised method for the assessment of environmental emissions incorporating pollution and emissions throughout the lifetime of a product. The longer term consequences can subsequently be reported as disability adjusted life years (DALYs). This study reported the climate change disability adjusted life years of echocardiography as 2.07 and MRI as 175 disability adjusted life years. Highlighting that MRI has 85 times the environmental impact of echocardiography, which causes the least environmental impact at each stage of its life cycle.

4. Discussion

The findings of this systematic review highlight that cardiac imaging has a significant environmental impact, which varies by modality: lowest for echocardiography and highest for MRI.

With the increasing demand for diagnostic imaging within cardiovascular healthcare it is becoming increasingly relevant to consider the environmental impact of these tests. Based off this review, we identify several areas where change could improve the environmental sustainability of cardiac imaging without compromising patient care (Fig. 2 and visual abstract). These themes relate to energy consumption, conscious contrast media usage, quality improvement strategies, and healthcare worker education.

4.1. *Reduce energy consumption*

As MRI becomes more accessible with increasing utility, considerations need to be made regarding appropriate usage. MRI has

Table 1
Details of included studies.

Author/year/ country	Study type	Study Aims	Method used to assess environmental impact	Results by imaging modality				Environmental impact	Key findings/summary
				Ultrasound	MRI	CT	Nuclear		
Anudjo 2023, UK (6)	Systemic literature review	Assess evidence of current environmental sustainability in radiology departments and provide a guide for greener practice	Various	Typical energy consumption760kWh/yr	111,000kWh/yr. 1/3rd of the consumption resulted from consumption during the system off state owing to helium cooling and cooling head operations.	41000kWh/yr. 2/3rds of CT energy consumption emanated from energy consumed during the non-productive state. Globally approx. 300 million CT exams are performed annually, involving an est. volume of 10 million L of iodinated contrast media	Not assessed	Evaluated three themes. 1: environmental consumption and data storage practices, 2: Usage of clinical consumables and waste management practices, 3: Travel activities related to radiology and radiotherapy/ radiation oncology. Energy consumption was derived to correspond to CO2 emission. Est 10 % of total carbon emissions are attributed to the healthcare sector.	Turning off work stations after core working hours reduced total energy consumption by ~5.6 %. This corresponds to a saving of 3.2 t of CO2 emissions. Energy losses during out-of-hours setting was estimated to be at 6656KWh and 27,452KWh per year. Radiological data storage and transfer (including redundant and supplicate data) utilises significant amounts of energy consumption. Data alongside cooling systems account for approximately 86 % of energy transmitted to radiology departments. Radiological data centres consume large volumes of water, estimated at 626 billion gallons *per annum*.
Marwick, 2011, USA (7)	Comparative life cycle assessment (LCA)	Assess the environmental impact of MRI, single photon emission tomography and cardiac ultrasound for the diagnosis of coronary artery disease.	Life-cycle assessment (LCA), potentially displaced fraction of species (PDF x mˆ2) and disability adjusted life years (DALY).	USS: 0.054 PDF x mˆ2 (0.5–2 % the damage of MRI); Climate change: 2.07 DALY; Ecotoxicity 0.03 PDF x mˆ2	MRI: 2.215 PDF x mˆ2; Climate change 175 DALY; Ecotoxicity 1.08 PDF x mˆ2 / year	Not assessed	Nuclear: 0.285 PDF x mˆ2 (4–11 % damage of MRI); Climate change 15.1 DALY; Ecotoxicity 0.23 PDF x mˆ2 / year	MRI was shown to be a major contributor to environmental impact based on LCA, DALY and PDF	Echocardiography resulted in the least environmental impact at each stage of its life cycle. Standby energy loss for all imaging modalities is a significant contributor to environmental disturbance (38 % of MRI energy use occurs in the unproductive state). The aggregate impact if undergoing echo was 1.5 % of an MRI and 14 % of SPECT. The main determinant in variation of damage was the difference in electricity requirements. For MRI

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Table 1 (*continued*)

Author/year/country	Study type	Study Aims	Method used to assess environmental impact	Results by imaging modality				Environmental impact	Key findings/summary
				Ultrasound	MRI	CT	Nuclear		
									98 % of damage was secondary to electricity use.
Braga, 2013, Italy (4)	Systemic literature review	Develop a comprehensive assessment of the 'true' cost of medical imaging including environmental damage from imaging paraphernalia and radioactive waste	CO2 Emission	CO2 emissions per exam 2.2 kg in Italy and 2.9 kg in USA	229 kg in Italy and 302 kg in USA of CO2 Emission per exam	Not assessed	Not assessed	CO2 Emissions were greatest with the use of MRI	Cardiovascular exams represent almost 30 % of the total exams acquired annually worldwide. Energy consumption from imaging methods corresponds up to 80 % of environmental impact on LCA (life cycle assessment)
Barratt 2023, USA (13)	Systematic review	To review studies assessing the environmental impacts, including carbon dioxide emissions of contemporary cardiovascular healthcare of all types.	Various, including CO2 emissions, DALY and LCA	Echo based imaging was found to have 1–20 % the environmental impact on human health, ecosystems and resource usage of those of cardiac MRI and nuclear based imaging base don LCA	Not assessed	Not assessed	Not assessed	All study aims reflected the importance of the need to consider and assess the environmental impact of cardiovascular healthcare, with the goal of improving sustainability.	A review of medical imaging in 10 diagnostic imaging categories found that the greatest opportunity to reduce energy consumption lay within cardiac imaging. Suggestions for improvement include using echocardiogram as the first-line test before considering MRI or nuclear studies. Alongside the implementation of simple, low-cost interventions such as quality improvement programs aimed at cutting unnecessary test ordering.
Picano, 2022, Italy (14)	Educational review	To highlight the economic, environmental and ethical consideration of cardiac imaging modalities and improve guidelines	CO2 Emission	2 kg CO2 emissions per exam	200-300 kg CO2 emissions per exam	20-30 kg CO2 emissions per exam	20-30 kg CO2 emissions per exam	Overall carbon footprint attributed to health care ranges from 4 % in the UK to 10 % in the USA. Medical imaging accounts for approx. 10 % of the healthcare footprint.	Over the last decade the cardiology imaging field has made significant improvements in patient and physician safety with a 10-fold reduction in radiation doses used across radiology, intervention and nuclear cardiology. However, more needs to be done to consider environmental sustainability in the cost-benefit analysis of medical imaging. The use of a sustainability index where in the ratio

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Table 1 (*continued*)

Author/year/country	Study type	Study Aims	Method used to assess environmental impact	Results by imaging modality				Environmental impact	Key findings/summary
				Ultrasound	MRI	CT	Nuclear		
									of accuracy to immediate cost (monetary), radiation risk (millisievert per exam) and carbon cost (kg of carbon dioxide emissions) should be considered.
Qin, 2022, UK (8)	Literature review	Evaluate the technical, practical and cost considerations of low-field MRI and to explore the barriers of implementing sustainable MRI.	Low field (1.5 T) MRI compared to high field (3 T) MRI in relation to cost, imaging quality, resources and environmental sustainability	Not assessed	Generation of upcoming 1.5 T scanner which employ new helium gas technology designed to conserve power and scan 4× faster than 3 T scanners.	Not assessed	Not assessed	New generation 1.5 T MRI scanners would benefit communities from a social, economic and environmental perspective.	With the ever increasing global demand for diagnostic imaging, coupled with growing concerns about climate change and helium shortages, it is critical for the MRI community to invest in sustainable technology to meet this demand, while minimizing the environmental impact.
Chaban 2023, USA (9)	Systematic review	Discuss the challenges, opportunities and the need for action to reduce the environmental impact of MRI including the preservation of finite resources, and development of adaption plans to prepare for the impact of climate change.	CO2 emissions and energy consumption	Not assessed	Substantial demand on electricity, contamination of water bodies related to gadolinium based contrast and the utilisation of finite resources of helium. Estimated energy expenditure on MRI in the USA is 1648kWh per year, The production phase (raw materials to delivery) consumes 2.73 million MJ (753,000 kWh) of fossil fuels. Use phase (electricity use from installation to decommission), MRI emissions average 20 kg CO2 equivalents (CO2e) per exam (6 kg CO2e for production and 14 kg for use phase). A typical MRI scanner operates with ~1500–2000 L of	298kWh energy consumption per 1000 people per year	Not assessed	If the health care sector were a country, it would be the 5th largest contributor to GHG emission on the planet accounting for 4.0–8.5 % of GCG emissions. Radiology and medical imaging departments account for up to 1 % of the global GHG emissions. The estimated annual electricity use of a single MRI machine is equivalent to 26 4-person homes.	The environmental sustainability of MRI can be broadly categorised into 3 groups. 1: strategies to reduce GHG emissions from MRI during production and use. 2: Other approaches to reduce the environmental impact of MRI including preservation of finite resources and mitigation of waterbody contamination 3: Development of adaptation plans to prepare for the impact of climate change in health systems and MRI departments Strategies to reduce GHG emissions from MRI include optimizing protocols and pulse sequences, reducing low value imaging, decreasing energy use in

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Table 1 (*continued*)

Author/year/ country	Study type	Study Aims	Method used to assess environmental impact	Results by imaging modality				Environmental impact	Key findings/summary
				Ultrasound	MRI	CT	Nuclear		
					liquid helium and uses up to 10,000 L over its 13y lifetime				idle and off states and reducing waste.
Dekker 2022, Netherlands (11)	Educational review	To raise awareness of the opportunity to make more conscious decisions regarding the use of contrast media and its disposal.	Volume of contrast media used and detected in waterways	Not assessed	Not assessed	10 million Litres of ICM are used globally every year.	Not assessed	Iodinated contrast media (ICM) breakdown products are toxic. ICM's have a high water solubility and metabolic stability which make them difficult to remove during the drinking water purification process. Commonly used drinking water purification techniques are not sufficient to effectively remove ICM. More conscious decisions regarding the use of contrast media need to be made.	Ways in which we can reduce the use of contrast media include personalized volumes, low-kV techniques, dual energy scanning with reconstruction of low-keV images and the contrast boost technique for CT angiography. Tailored bottle sizes of contrast media and contrast disposal techniques.

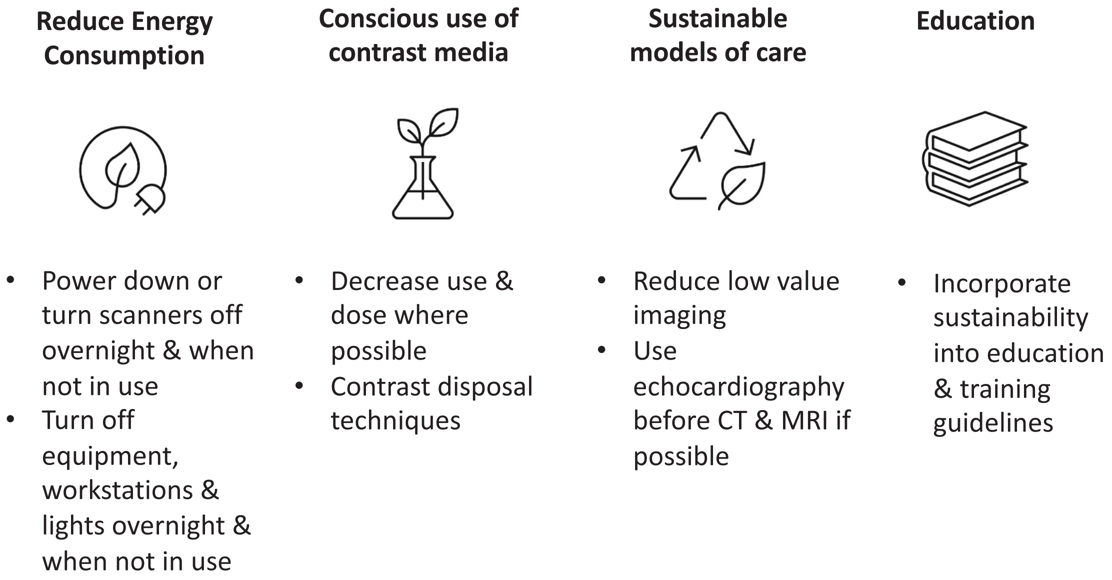

Fig. 2. Summary of key areas to focus on for environmental sustainability of cardiac imaging.

considerable energy consumption, of which a great proportion (38 % Marwick *et al*) is consumed during the unproductive state. Educating and alerting operators to initiate 'power-off' states with 7–10 kW energy consumption in comparison to 29-48 kW in 'scan' mode and 10-15 kW in 'idle' mode [7]. Over the lifetime of the device this would contribute to significant energy consumption savings. This same principle applies to all imaging modalities as well as reporting stations such as desktop computers, when not actively in use. Additionally, there is increasing use of 'Ultrafast' and 'Single Breath Hold' cardiac MRI protocols [11]. These protocols are effectively reducing active acquisition time and thus energy consumption, without compromising image quality and diagnostic accuracy. Even more modest protocol changes can reduce energy including moving cine SSFP sequences after contrast administration to minimize idle time, with a recent study demonstrating that this change could avoid 13,200 kWh energy and 5600 kg CO_2e per year [12]. There is also growing interest in leveraging artificial intelligence to accelerate image acquisition and de-noise these accelerated images [13].

The usage of helium, a non-renewable form of energy, within MRI imaging contributes to its environmental footprint. The incorporation of 1.5 T superconducting magnets using cryocooling technology is highlighted by Qin et al. [8] These scanners are designed to conserve power, non-renewable resources, and reduce scan time significantly. Additionally, further research is required to expand cardiac imaging to low-field MRI technology to capitalise on the environmental benefits.

4.2. *Conscious use of contrast media*

It is estimated that 10 million litres of iodinated contrast media (ICM) are used globally each year [14]. ICM is known to have a high water solubility and metabolic stability which renders the content difficult to remove during purification techniques. This ultimately results in potentially toxic breakdown products of ICM entering waterways. The same should be considered for gadolinium-based contrast agents used with MRI. End-of-pipe water treatments are increasingly known to degrade these agents, which increases their potential adverse health effects [15].

Contrast usage can be minimised through a number of techniques including personalized volumes, tailored bottle sizes, and contrast disposal techniques including post-scan urination collection. Additionally, dual energy scanning with reconstruction of low-keV images and the contrast boost technique for CT angiography can reduce the required volume of contrast media while ensuring diagnostic quality imaging. Also, implementing policies that aim to promote conscious use of contrast media may be helpful, including the appropriate ordering of contrast-based scans.

4.3. *Sustainable models of care*

This is about reducing low value care while optimizing quality. The utilisation of a sustainability index within cardiac imaging healthcare should be considered [16]. This index is a resource which may enable physicians to make informed decisions regarding imaging requests. The sustainability index is a ratio of accuracy to immediate cost (monetary), radiation risk (millisievert per exam) and carbon cost (kg of carbon dioxide emissions). Therefore providing a simple measure of sustainability of an individual test which is both easy to interpret but also allow for direct comparison. Potential implementation models include 'traffic light' systems, or more labour intensive questionnaires which may more directly highlight the implications of some test types. More broadly, the triple bottom line framework of sustainability can be applied in cardiac imaging to optimize health outcomes while minimizing the environmental, social and financial costs of delivering care [17].

4.4. *Education*

In line with sustainable models of care, physician and healthcare worker education regarding sustainability is imperative and should be incorporated into education and training guidelines [18]. Education and quality improvement for the physician is an imperative component of best practice. The incorporation of quality improvement into environmental sustainability is imperative to the long term impact of cardiovascular healthcare. This can be used to develop scanning protocols and ordering guidelines aimed at reducing unnecessary and inappropriate orders, to reduce low value imaging. Barratt *et al* details the incorporation of quality improvement to guide test ordering resulting in reduced costs, waste and carbon emissions [19]. Given echocardiography resulted in the least environmental impact at each stage of its life cycle [7] and was replicated throughout the studies in this review, it can be deduced that utilising environmentally sustainable modalities in the first instance, if appropriate to answer the clinical question, would result in a lower environmental footprint.

Highlighting the environmental footprint to referring doctors could also be done by including an estimate of the environmental footprint of a scan in the final formal report, much like is done with reporting radiation exposure in cardiac CT reports.

4.5. Limitations

This study has inherent limitations which should be considered, including the small number of papers included for final analysis. This reflects the small but emerging field of the environmental impact and sustainability specifically within the cardiac imaging sector. Additionally, the heterogeneity of study types and data collected in this systematic review meant quantitative assessment was unable to be performed. Thus, it is evident that more research is required within this field.

Furthermore, there are limitations to the assessment techniques used for example, the life cycle assessment (LCA) relies on generalized data sets, which may not be applicable to all study populations; and it uses a number of energy metrics, which may result in the energy intensity reported not correlating to the required energy input of a product or process as a result of other factors such as the materials used [20]. However, the LCA methodology remains one of the best tools to evaluate the environmental sustainability of products, processes and services considering all phases from extraction of raw material to end-of-life. Unfortunately only one study in this review used this assessment. We also note the inherent assumptions embedded within the DALY measurement, both descriptive and evaluative. These assumptions, although not limited to 'health vs well-being' are known to modify both the size and distribution of disease burden [21].

5. Conclusion

Non-invasive cardiac imaging has a significant environmental impact, which varies by modality: lowest for echocardiography and highest for MRI. This review details several strategies in which cardiovascular imaging can reduce its environmental footprint. Appropriate and conscientious usage of resources is imperative to environmental sustainability.

Disclosures

Nil.

CRediT authorship contribution statement

Kelsey Gardiner: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Kate Hanneman:** Writing – review & editing. **Rebecca Kozor:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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