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Review

The Green Print: Advancement of Environmental Sustainability in Healthcare

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ABSTRACT

Healthcare is a major emitter of environmental pollutants that adversely affect health. Within the healthcare community, awareness of these effects is low, and recognition of the duty to address them is only beginning to gain traction. Healthcare sustainability science explores dimensions of resource consumption and environmental emissions associated with healthcare activities. This emerging field provides tools and metrics to quantify the unintended consequences of healthcare delivery and evaluate effective approaches that improve patient safety while protecting public health. This narrative review describes the scope of healthcare sustainability research, identifies knowledge gaps, introduces a framework for applications of existing research methods and tools to the healthcare context, and establishes research priorities to improve the environmental performance of healthcare services. The framework was developed through review of the current state of healthcare sustainability science and expert consensus by the Working Group for Environmental Sustainability in Clinical Care. Key recommendations include: development of a comprehensive life cycle inventory database for medical devices and drugs; application of standardized sustainability performance metrics at the clinician, hospital/health system, and national levels; revision of infection control standards driving non-evidence-based uptake of single-use disposable devices; call for increased federal research funding; and formation of a Global Commission on the Advancement of Environmental Sustainability in Healthcare. There is an urgent need for research that informs policy and practice to address the public health crisis arising from healthcare pollution. A transformational vision is required to align research priorities to achieve a sustainable healthcare system that advances quality, safety and value.

1. Introduction

Pollution is a leading cause of morbidity and mortality, globally responsible for 9 million premature deaths in 2015, or 16% of all deaths (Landrigan et al., 2018). Most of these environmentally-mediated deaths are presently linked to air pollution, responsible for 1 in 8 deaths globally (Cohen et al., 2017). Climate change resulting from greenhouse gas emissions has been named the number one public health issue of the 21st century, and like air pollution, predominantly stems from fossil fuel combustion (Costello et al., 2009). An estimated 150,000 deaths occur annually worldwide due to climate change-mediated health hazards such as extreme weather events, worsening air quality, food and water-borne illnesses, vector-borne diseases, food and water insecurity, and social instability. Loss of an additional 250,000 lives per year is projected to occur between 2030 and 2050 from climate change (World Health Organization 2009), and critical earth systems will be further disrupted in decades to come unless significant action to mitigate emissions is taken urgently (Steffen et al., 2015). At the same time that health professionals strive to help patients cope with the adverse health effects of pollution, health professional leadership is essential to draw attention to these effects, and to help identify and prioritize mitigation strategies (Costello et al., 2009; Costello et al., 2013). Ironically, modern healthcare itself is a major emitter of environmental pollutants that adversely affect human health (Eckelman and Sherman, 2016; Eckelman and Sherman, 2018; Eckelman et al., 2018; Malik et al., 2018; National Health Service Sustainable Development Unit, 2016). Awareness of healthcare pollution and the duty to address it are only beginning to gain recognition in the clinical community.

In *Crossing the Quality Chasm* in 2001, the Institute of Medicine described specific aims for building quality as a health systems property that include: avoiding injuries to patients from care that is intended to help them, improving efficiency, and avoiding waste (Institute of Medicine Committee on Quality of Healthcare in America, 2001). Yet the United States healthcare sector alone is responsible for emitting 9% of criteria air pollutants and 9-10% of greenhouse gases nationally, as well as other toxic emissions, resulting in loss of 614,000 Disability-Adjusted Life Years (DALYs) annually (Eckelman and Sherman, 2016; Eckelman and Sherman, 2018). This indirect disease burden is commensurate with preventable medical errors as first reported by the Institute of Medicine in *To Err is Human* (Kohn et al., 2000) that gave rise to the patient safety movement (Eckelman and Sherman, 2016), but is presently unaccounted for. In 2013, the Institute of Medicine Roundtable on Environmental Health Sciences Research and Medicine suggested that the health sector lead by example by reducing its ecological footprint to improve human and planetary health (Institute of Medicine Roundtable on Environmental Health Sciences Research and Medicine, 2013). Efforts to frame healthcare pollution as a matter of patient safety (Eckelman and Sherman, 2016) are just getting underway so that environmental performance is adopted into continuous quality performance improvement mandates (Sherman and Lagasse, 2018; Sherman et al., 2019). Focusing on sustainability efforts within healthcare delivery, specifically clinical care, has the potential to engage health professionals. Health professional leadership can then serve as a force multiplier to engage administrators, policy makers, as well as the patients served, to more urgently address pollution threats to health and well-being globally.

2. Approach

The aims of this narrative review were to describe the scope of healthcare sustainability research, identify research gaps, suggest an emerging framework for research methods and tools, and identify research priorities to help foster improvement in the environmental performance of healthcare services. For the purposes of this review, sustainability was defined using Our Common Future (Brundtland, 1987), and the common frameworks of the Triple Bottom Line (Elkington, 1999) and the United Nation's Sustainable Development Goals (UN SDGs) (United Nations, 2020). Here, we choose to focus primarily on environmental sustainability. The topic of sustainable healthcare has expanded considerably in recent years (Cimprich et al., 2019; Alshqaqeeq et al., 2020), yet few articles have summarized the field holistically. This narrative review of literature was conducted to identify key studies in preparation for the Workshop on Environmental Sustainability in Clinical Care. During the workshop, the Working Group reviewed the current state of healthcare sustainability science and developed recommendations through consensus-based discussions. This narrative is organized first by the current state in the

Table 1
Key Research Gaps and Priorities for Environmental Sustainability in Clinical Care.

Safety, quality and value in healthcare
Pollution and climate change are contributing to a global health crisis.
Pollution itself is a patient safety issue, and pollution prevention should be included in efforts to improve healthcare quality.
Clinical activities are the major driver of resource utilization and waste in health care and provide a fundamental opportunity for engaging health professionals in pollution prevention efforts.
Healthcare emissions research
Strategic areas of investigation include: basic materials management, pharmaceuticals and medical device design, environmentally preferable clinical care pathways, hospital/health systems and provider-level performance metrics with international benchmarks.
A new life cycle inventory database containing whole medical products (pharmaceuticals and medical devices) is needed to facilitate research and development of best practices. Such a tool should be integrated into electronic health records and procurement information management systems to support environmentally preferable practices and performance benchmarking.
Translational science must include application of existing metrics that measure environmental performance. Such metrics should then be embedded into existing quality and safety reporting frameworks, including remuneration models.
The study of clinical best practices should be expanded to include optimization of resource efficiency and pollution prevention, in addition to patient outcomes.
Reporting guidelines for healthcare sustainability research also need to be developed. This can be achieved through the Enhancing the Quality and Transparency Of health Research (EQUATOR) network for other types of translational research (UK EQUATOR Centre, 2020).
Implementation, benchmarking and accountability
Partnership is called for between healthcare sustainability experts and patient safety experts. Safety and quality organizations such as the Institute for Healthcare Improvement (IHI), the National Patient Safety Foundation (NPSF), the Anesthesia Patient Safety Foundation (APSF), and others should work to advance the synergistic agenda around resource stewardship.
Excessive infection control standards and practices without sufficient evidence are viewed as a major driver of avoidable pollution and waste generation in healthcare. Engagement of accrediting agencies and regulatory bodies is essential to minimize unintended adverse environmental effects as a result of care that offers no proven patient benefit.
The evidence-based, best practices identified by initiatives like Choosing Wisely, Getting it Right the First Time, and the Wise List must include environmentally preferable, in addition to waste-sparing, practices. Partnerships with these organizations are recommended to mainstream environmental stewardship into the healthcare quality discourse.
Integrating environmental sustainability into value-based healthcare reform, and communicating with clinicians and policy makers in the language of these paradigms, can help to achieve rapid uptake and success of healthcare sustainability initiatives.
Research funding for sustainable clinical care
Government funding agencies, e.g. the National Science Foundation, the National Institutes of Health, and the Agency for Healthcare Research and Quality, and philanthropic foundations, should create funding mechanisms that bridge environmental sustainability science with health services research to translate knowledge into sustainable clinical practices.
Formation of a Global Commission on the Advancement of Environmental Sustainability in Healthcare, e.g. through the National Academies of Science, Engineering and Medicine (NASEM) is called for to further research efforts that inform policy and practice, and urgently focus leadership on the pollution public health crisis.

The Workshop on Environmental Sustainability in Clinical Care (The Workshop on Environmental Sustainability in Clinical Care), held at Yale University in New Haven, CT USA April 4-6 in 2018, co-hosted with New York University, brought together international experts in engineering, sustainability science, clinical care, and health systems management to explore issues of resource consumption and environmental emissions associated with healthcare services. This Working Group discussed current research in clinical sustainability, future research objectives and best practices, methods of safely and broadly implementing evidence-based metrics to encourage integration of sustainability science within standard healthcare operations, and educational requirements to support the advancement of this emerging interdisciplinary field.

areas of healthcare emissions research, implementation, benchmarking and accounting, and education. Next, research gaps and priorities were identified. Finally, outcome recommendations, summarized in Table 1, and overarching conclusions are presented.

3. Healthcare emissions research

There are growing efforts internationally to measure and mitigate healthcare environmental emissions, with particular emphasis on greenhouse gases (World Bank, 2017; World Health Organization, 2017; Watts et al., 2017). In 2009, the United Kingdom Sustainable Development Unit first reported its National Health Service (NHS) England greenhouse gas emissions, and now publishes updates every 2-3 years (Sustainable Development Unit, 2018). After instituting a national-level benchmarking system, NHS England has documented an 11% reduction in greenhouse gas emissions from healthcare activities between 2007 and 2015 despite increased utilization of health services during this time. NHS England reports that it is on track to meet short term targets, and is moving toward the mandate of 80% emissions reduction by 2050 as set forth by the United Kingdom Climate Change Act of 2008 (National Health Service Sustainable Development Unit, 2016). Further, the NHS recently announced its ambition to achieve 'net zero' carbon emissions, well ahead of its legal mandate (National Health Service, 2020). National estimates of health sector greenhouse gas emissions have been performed for several other developed nations including the United States (Eckelman and Sherman, 2016; Chung and Meltzer, 2009), Australia (Malik et al., 2018), Sweden (Swedish Municipalities and County Council, 2017), Canada (Eckelman et al., 2018), Japan (Nansai et al., 2020), Austria (Weisz et al., 2020), and China (Wu, 2019). However, only the NHS has an ongoing initiative to mitigate and measure carbon emissions progress. With methodological standardization, it is expected that measuring and reporting health sector emissions will allow for useful comparisons between and within countries. Such metrics should include both healthcare environmental emissions and their associated disease burden. These metrics should be normalized with quality measures that reflect costs and population health, to inspire widespread improvements and greater international accountability, particularly as pollution fails to respect national geographic boundaries (Eckelman et al., 2018).

Within the health sector, significant fractions of environmental emissions stem from upstream manufacturing, utilization, and downstream disposal of pharmaceuticals and medical devices (Malik et al., 2018; National Health Service Sustainable Development Unit, 2016; Eckelman and Sherman, 2016). Life cycle assessments (LCAs) of the emissions associated with these products are required to guide evidence-based decision-making for clinicians and health administrators (National Health Service, 2012). A growing body of clinically relevant environmental impact studies includes: anesthetic equipment and pharmaceuticals (McGain et al., 2010; Eckelman et al., 2012; Sherman et al., 2012; McGain et al., 2017; Alexander et al., 2018; Sherman et al., 2018; McAlister et al., 2016; Parvatker et al., 2019; Sanchez et al., 2020), central venous catheters (McGain et al., 2012), dental burs (Unger and Landis, 2014), disposable surgical custom packs (Campion et al., 2015), surgical instruments (Adler et al., 2005; Unger et al., 2017; Siu et al., 2016; Manatakis and Georgopoulos, 2014; Yung et al., 2010; Davis et al., 2018), medical grade plastics (Unger et al., 2017), hospital gowns and textiles (Hicks et al., 2016; Overcash, 2012; Dettenkofer et al., 1999), and radiology equipment (Esmaeili et al., 2011; Cimprich et al., 2018). Studies of entire clinical services or care pathways include: birth procedures (Thiel et al., 2012), hysterectomy (Thiel et al., 2014), hemodialysis and peritoneal dialysis (Connor et al., 2011; Dunbar-Reid and Buikstra, 2017; Lim et al., 2013; Chen et al., 2016), plastic surgery (Berner et al., 2017), cataract extraction (Venkatesh et al., 2016; Morris et al., 2013), laparoscopic and minimally invasive procedures (Woods et al., 2015; Power et al., 2012), ambulance services (Brown et al., 2012), intensive care (Pollard et al., 2014; Huffling and Schenk, 2014), dental services (Duane et al., 2017; Duane et al., 2012), perioperative services (MacNeill et al., 2017), and telehealth (Holmner et al., 2014; Wootton et al., 2010; Pollard et al., 2019). These studies are useful in identifying pollution hot spots and comparative advantages of some clinical alternatives; however, information and scientific standards gaps thwart implementation of performance improvement efforts.

3.1. Healthcare sustainability science framework

A comprehensive approach to healthcare environmental emissions research, including analytical methods and tool development, is needed to better evaluate clinical materials and processes, and aid in the development of performance metrics to guide and track progress. An integrated discipline, often referred to as 'healthcare sustainability', is evolving that includes contributions from the fields of industrial and environmental engineering, sustainability science, medicine, nursing (Anaker and Elf, 2014; St Pierre Schneider et al., 2009), public health, healthcare economics and health systems management, with variability across countries (Borgonovi et al., 2018). Healthcare sustainability science explores dimensions of resource consumption and environmental emissions associated with healthcare activities, with the aim of improving the quality, safety and value.

The industrial ecology framework seeks to develop solutions and strategies that eliminate waste and pollution from human systems, keep products and materials in use, and regenerate or renew natural systems. LCA is the predominant analytical tool employed to analyze healthcare sustainability (Sustainable Development Unit. Coalition for Sustainable Pharmaceuticals and Medical Devices, 2019; Sustainable Development Unit, 2012). LCA is an internationally standardized scientific approach (ISO 14040 (International Organization for Standardization. ISO 14040 1997)) used across many industries to quantify emissions of a product or process over its entire life cycle. The total life cycle can account for inputs, emissions and subsequent health impacts from "cradle-to-grave", including extraction of natural resources, manufacturing, transport, use/re-use, and disposal or end of life. In this way, LCA includes direct emissions from product use, along with indirect emissions from activities upstream (i.e., the supply chain production and transportation) and downstream (i.e. waste disposal management). LCA enables comparisons between alternative products and processes and thus can be used to inform healthcare decision-making.

LCA and other industrial ecology methods and tools, such as circular

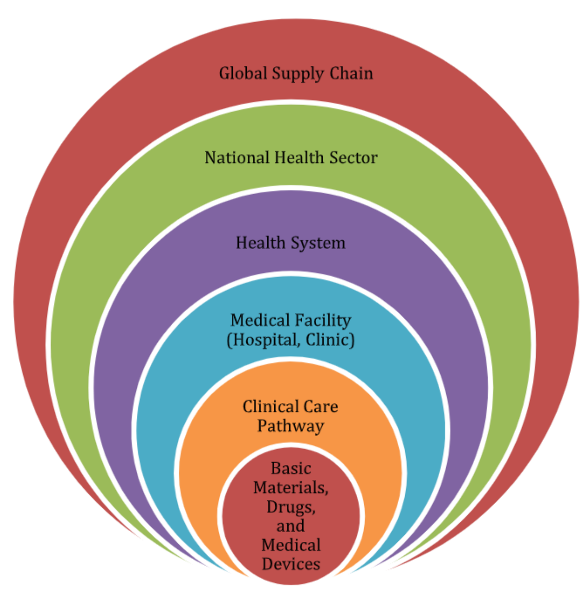

Figure 1. Sustainable healthcare emissions research framework

economy, can be used to further assess healthcare services at multiple levels, including: global supply chain, national healthcare systems, whole hospital/health systems, clinical pathways and procedures, individual drugs, medical devices, and basic materials, (figure 1). A healthcare-specific industrial ecology framework that unifies top-down (macro scale) and bottom-up (micro scale) approaches is needed, to contextualize clinical activities, and to improve the overall utility of research that seeks to guide implementation efforts and track healthcare environmental performance improvement.

3.2. Top-down studies: health sectors and systems

Top-down national-level approaches serve to describe the quantities and types of health sector emissions and can be extended to estimates of secondary health damages for a given country (Eckelman and Sherman, 2016; Eckelman et al., 2018; Malik et al., 2018; National Health Service Sustainable Development Unit, 2016; Chung and Meltzer, 2009; Weisz et al., 2020; Nansai et al., 2020; Wu, 2019). National-level studies aid in identifying major categories of environmental concern, such as pharmaceuticals and medical devices. Comparisons between nations of similar economic development and health system architectures are possible (Hertwich and Peters, 2009). However, due to differences in national health expenditure accounting or the macro-level emissions models used, the utility of direct comparisons between these individual studies is limited. A single framework is needed for approaching national-level benchmarking and comparisons, that includes standardized methods and models, action-oriented environmental emissions reporting categories, and ideally includes disease burden. Such a uniform framework could help drive international healthcare quality performance improvement (Watts et al., 2018), analogous to the Global Burden of Disease initiative by the Institute for Health Metrics and Evaluation (Institute for Health Metrics and Evaluation 2019). International studies are beginning to appear in the literature (Pichler et al., 2019; Health Care Without Harm, 2019; Watts et al., 2019), and health sector metrics are now integrated into the annual report of the Lancet Commission on Health and Climate Change (Watts et al., 2019). The aggregated nature of data used to perform such top-down investigations necessitates additional bottom-up studies of clinical activities in order to assess drivers of and solutions to pollution and wasteful practices.

Health systems and hospital/clinic level sustainability benchmarking is a strategic research area. Such assessments are emerging, notably in the United Kingdom where reporting is now compulsory for the Estate Return Information Collection (ERIC) statistics (National Health Service, 2018) on facility-level energy, water, and waste management metrics. In the United States, Kaiser Permanente (Permanente, 2018), Cleveland Clinic (Cleveland Sustainability, 2017), and Gundersen Health (Gundersen Health, 2018) are sustainability exemplars that measure and mitigate emissions. Though facility management tools may help with reporting metrics related to energy consumption (Brambilla et al., 2019; Phiri and Chen, 2014), no single reporting structure prevails. Existing corporate social responsibility (CSR) reporting methods such as The Climate Registry (Needy et al., 2007), Carbon Disclosure Project (2020), and the Global Reporting Initiative (Global Reporting, 2020) include sustainability metrics that can be useful to health systems; (Sherman and Lagasse, 2018; Senay and Landrigan, 2018) however, reporting is voluntary, and there is no standardized approach specific to the needs of health institutions. Importantly, with the exception of some local initiatives that track usage of inhaled anesthetics (which are potent greenhouse gases), and remanufactured (a.k.a. reprocessed) medical devices, facility-level environmental metrics do not currently reflect specific clinical activities and health outcomes. Material flow analyses of the supply chain within health service lines, and between providers, are needed to aid in identifying clinical priority areas.

3.3. Bottom up studies: clinically relevant research

Clinical bottom-up research is essential to understand both drivers of and solutions to environmental emissions, as clinical activities are the major driver of resource utilization in healthcare. Interdisciplinary sustainability scientist and clinician research collaboratives help ensure that studies are both clinically relevant and measured appropriately.

3.3.1. Medical products

To support process-based clinically relevant applications, research on healthcare product materials (Unger et al., 2017; Albert et al., 2018; Marie et al., 2017; Nardelli et al., 2017; Graedel et al., 2015) and on green design that facilitates safe reprocessing/reuse of products and materials is needed. The growing prevalence of single-use disposable products is of growing concern. Plastic is ubiquitous in medical products, and recycling is challenging for several reasons including: concern for infection prevention, complex material combinations, and insufficient processing infrastructure. Plastic materials are derived from fossil fuels, and persist long-term in the environment. While waste-to-energy incineration is becoming more popular, traditional incineration is still common (especially in the developing world) and releases concerning toxicants such as dioxins and heavy metals. Plasticizer additives are known endocrine-disrupters that persist in the environment and bioaccumulate (Li et al., 2016). Comparisons between reusable devices with disposable single-use and reprocessed single-use devices, as well as supply utilization patterns, are critically important to develop opportunities that reduce pollution and resource consumption, and to identify areas in need of design improvement (Sherman et al., 2019).

3.3.2. Pharmaceuticals

Pharmaceuticals are responsible for large fractions of healthcare emissions, including 10%, 18%, and 25% of national health sector life cycle greenhouse gas emissions alone in the United States (Eckelman and Sherman, 2016), Australia (Malik et al., 2018), and Canada (Eckelman et al., 2018), respectively. Describing environmental footprints of pharmaceuticals and their clinical alternatives is particularly useful to support clinical decision-making (Sherman et al., 2012; Castensson et al., 2009). Such research is hampered by insufficient life cycle inventories (LCI) of drugs (Parvatker et al., 2019). Some pharmaceutical companies may elect to self-report LCIs of active pharmaceutical ingredients (Sustainable Development Unit, 2016). However, such reporting is insufficient, lacks standardization, and requires third-party verification.

Waste of opened and unused pharmaceuticals is substantial, driven in large part by manufactured package sizes designed and incentivized to be larger than required by a single patient (Atcheson et al., 2016; Bach et al., 2016) combined with regulations deterring safe splitting between patients into unit doses (Centers for Disease Control, 2019). Investigation of opportunities that conserve resources should include evaluation of regulatory drivers of waste, assessments of unused wasted supplies and their environmental and cost impacts, to improve motivation for process improvement.

3.3.3. Alternative clinical care pathways and best practices

The concept of “clinical best practices” is beginning to expand from optimizing patient outcomes to include notions of resource efficiency and pollution prevention (Sherman et al., 2019; Mortimer et al., 2018a; Mortimer et al., 2018b). The Choosing Wisely (American Board of Internal Medicine Foundation, 2018) campaign of the American Board of Internal Medicine seeks specialty-specific guidance on identifying evidence-based initiatives to reduce unnecessary testing and treatments and iatrogenic harms, and to conserve healthcare resources. A similar, or expanded, approach to include sustainability initiatives can help direct research, and encourage clinician engagement and specialty-specific innovation at the point of care delivery. Environmental impact research can add motivation for addressing the overuse or misuse of clinical resources while increasing awareness of the pollution and public health impacts of clinical care.

Frequently, multiple approaches to safe clinical care are possible. Where clinical equipoise exists, environmental emissions should factor into clinical decision making; however, data are presently scant. One area where research has already influenced environmental practice is in the specialty of anesthesiology. Inhaled anesthetic drugs are potent greenhouse gases that are vented directly off of facility rooftops after use, where their emissions to the outdoor atmosphere are presently unregulated anywhere in the world. Higher than needed quantities of drugs (fresh gas flow rates and concentrations) are routinely used, driven by both antiquated regulations and provider habit. Research on life cycle greenhouse gas emissions of clinically relevant quantities of drugs noted that those from inhaled anesthetics vary by 20-fold between options (notably desflurane and nitrous oxide are the worst offenders). Further, life cycle greenhouse gas emissions of inhaled drugs are 4 orders of magnitude greater than a common intravenous alternative, propofol (Sherman et al., 2012; Thiel et al., 2014; MacNeill et al., 2017; Thiel et al., 2018). This finding has resulted in professional recommendations by both the American Society of Anesthesiologists Environmental Task Force and the Association of Anaesthetists of Great Britain & Ireland Environment and Sustainability Committee (American Society of Anesthesiologists, 2018; Association of Anaesthetists of Great Britain & Ireland, 2020), and has begun to affect change in clinical practice (Alexander et al., 2018). Several campaigns to reduce or eliminate the use of desflurane have already resulted in significant environmental and fiscal savings (Alexander et al., 2018).

Healthcare sustainability studies are beginning to draw lessons from global comparison of clinical practices, including between developed nations (MacNeill et al., 2017) as well as between developed and developing nations (Thiel et al., 2016). The efficiencies built into more resource-constrained systems provide instructive models of care for health systems in which waste and inefficiency are ingrained. For example, the United Kingdom-based cataract procedure is estimated to produce nearly 130 kg CO2e (Morris et al., 2013), whereas in India, the same procedure generates only 6 kg CO2e (Thiel et al., 2016). Both sites have comparable clinical outcomes (Haripriya et al., 2012), and the Indian site achieves this at about 1/10th the cost of the United Kingdom site (Venkatesh et al., 2016; Morris et al., 2013). Such findings have led to sustainable practice improvement recommendations by the Royal College of Ophthalmologists and the International Agency for the Prevention of Blindness environmental sustainability working groups (International Agency for the Prevention of Blindness, 2020). Carbon emissions metrics have now been added to the American Society of Cataract and Refractive Surgeons Ophthalmic Instrument Cleaning and Sterilization Task Force guidelines (Guidelines for the Cleaning and Sterilization of Intraocular Surgical Instruments, 2018).

In addition to anesthesiology (McGain et al., 2010; Eckelman et al., 2012; Sherman et al., 2012; McGain et al., 2017; Sherman et al., 2018; McGain et al., 2012; MacNeill et al., 2017; Thiel et al., 2018; American Society of Anesthesiologists, 2018; Association of Anaesthetists of Great Britain & Ireland, 2020; Sherman and Hopf, 2018; Sherman and Berkow, 2019) and ophthalmology (Venkatesh et al., 2016; Morris et al., 2013; Thiel et al., 2016; Thiel et al., 2017; Tauber et al., 2019), nephrology (Connor et al., 2011; Dunbar-Reid and Buikstra, 2017; Lim et al., 2013; Chen et al., 2016; National Kidney Federation, 2020) is another leading specialty seeking to advance sustainable practices. These specialties can serve as models for other health professional disciplines. The Centre for Sustainable Healthcare (Centre for Sustainable Healthcare, 2020) in Oxford, England, offers opportunities to partner clinical specialists and communities of care to generate evidence and devise specialty-specific best practice recommendations. Modifying the environmental footprint of clinical activities ultimately will require multilevel stakeholder engagement between clinicians and hospital administrators, professional societies, regulatory bodies and policy makers, and industry.

3.4. Research tools and reporting standards

Life cycle inventory (LCI, or “cradle to gate”) databases presently lack healthcare-specific items, including relevant chemicals and pharmaceuticals (De Soete et al., 2017; Geisler et al., 2004). In order to better account for emissions embedded within the global healthcare supply chain and various clinical practices across the planet, expanded LCI databases and impact assessment methodologies that enable international LCA comparisons are needed. An LCI database dedicated to whole medical products, including pharmaceuticals and devices, could facilitate clinical research and further enable widespread implementation of clinical performance benchmarking. The Product Category Rules (PCR) of the International Environmental Product Declaration (EPD) system (EPD, 2020) could serve as the framework for such a database, and encourage the broader adoption and reporting of environmental emissions assessments of products in the healthcare industry.

With wider implementation of electronic health records (EHR), supply chain, and building information management systems, the ability to access input data needed for quantitative assessment of materials utilization and associated environmental emissions is improving. Healthcare sustainability researchers can work with health administrators to generate relevant reports on energy and materials used for clinical care delivery. Standardization and automation of data collection and analytic processes can support LCA research, and facilitate more rapid implementation of environmental efficiency improvements into healthcare systems. Such tools should eventually be integrated into laboratory and treatment ordering systems and the EHR, where they can support clinician decision-making, as well as provide ongoing performance tracking (Sherman et al., 2019; Sherman and Berkow, 2019).

Agent-based modeling and other computational models can be incorporated into LCA and other environmental benchmarking assessments to evaluate dynamic patient care environments or medical delivery systems. For example, computational models can be used to calculate the environmental emissions of various approaches to rural healthcare including centralized secondary care facilities, decentralized outreach clinics, and telemedicine options (Duane et al., 2014; Pollard et al., 2013; Lo Presti et al., 2019). These can help inform health systems policies and growth strategies, incorporating the environmental footprint into needs assessments and systems planning.

Reporting standards for healthcare sustainability research do not presently exist. They can be achieved through creation of research guidelines that incorporate environmental sustainability metrics, and integration into the Enhancing the QUAlity and Transparency Of health Research (EQUATOR) network (UK EQUATOR Centre, 2020). Such a standard could include reporting of environmental emissions (e.g., carbon dioxide equivalents) with more generally accessible metrics such as “equivalent kilometers driven,” disease burden metrics such as Quality-Adjusted Life Years/ Disability-Adjusted Life Years (QALYs/ DALYs) when appropriate, and paired with healthcare outcomes. A web-based repository of existing sustainable healthcare literature, ongoing projects, and research method guidelines is presently lacking. Multiple frameworks already exist for such a tool, such as LCA-commons.gov, that may be expanded to serve this purpose.

4. Implementation, benchmarking and accountability

4.1. Creating and integrating sustainability metrics into existing performance improvement reporting systems

Development of a robust, standardized set of metrics that define environmental performance and gauge progress is required to optimize performance, and metrics must be normalized to allow for meaningful comparisons (Mortimer et al., 2018a). This must be accomplished on multiple scales, including for individual products, clinical care pathways, providers, entire hospitals and health systems, and national healthcare sectors. Various quality and safety reporting frameworks exist within the healthcare arena already. Integrating environmental performance metrics into existing reporting structures would be more efficient and effective than devising a parallel sustainability platform de novo.

Deriving and validating metrics is a rigorous science, best exemplified by the field of continuous quality improvement. As healthcare resources are increasingly strained, there is intensified interest at all levels of administration and care provision in accurate assessment and system performance feedback. This presents an opportunity to integrate environmental performance into existing hospital evaluation mechanisms. This can include building on mandatory reporting systems such as the Estates Return Information Collection (ERIC) (National Health Service, 2018) in the United Kingdom, The Joint Commission and other hospital accreditors (Centers for Medicare and Medicaid Services, 2018), the Hospital Consumer Assessment of Healthcare Providers and Systems (CAHPS) survey (Centers for Medicare & Medicaid Services, 2018), as well as voluntary systems such as Magnet Award status conferred by the American Nurses Credentialing Center in the United States (American Nurses Credentialing Center).

Continuous quality reporting and feedback programs are in widespread use in North America for perioperative services, and afford opportunity for environmental performance reporting. The National Surgical Quality Improvement Program (American College of Surgeons, 2018) administered by the American College of Surgeons is a risk-adjusted, outcomes-based program that aims to reduce post-operative complications and, by extension, cost. The synergies of these objectives with those of an environmental sustainability agenda lend themselves to incorporation of environmental performance reporting within this framework as another aspect of surgical quality. Similarly, the Multicenter Perioperative Outcomes Group Anesthesiology Performance Improvement and Reporting Exchange (Multicenter Perioperative Outcomes Group, 2017) provides clinician feedback on key management areas to inspire and track performance improvement. For example, there are a number of effective reduction strategies for inhaled anesthetic management advocated by professional societies such as the American Society of Anesthesiologists (American Society of Anesthesiologists, 2018) and the Association for Anaesthetists of Great Britain and Ireland (Association of Anaesthetists of Great Britain & Ireland, 2020). Given the robust body of work detailing the environmental impacts of various anesthetic modalities and intraoperative management, this framework is ideally situated to report hospital- and provider-level environmental performance data.

Another rich dataset into which clinical sustainability metrics could be embedded is the American Hospitals Association annual survey (American Hospitals Association , 2018). This is a serial cross-sectional study of the 6500 US hospitals, collecting longitudinal data regarding facilities and services, utilization, and physician arrangements and expenses, among other indicators. The American Hospitals Association launched the Sustainability Roadmap (The American Hospitals Association, 2015) with the American Society of Healthcare Engineering (ASHE), the Association for the Healthcare Environment, and the Association for Healthcare Resource and Materials Management. Several facility performance metrics are proposed, and currently there is opportunity to voluntarily report on building energy performance through ASHE's Energy to Care (the Energy Star Hospital program) (Energy, 2016). Practice Greenhealth (Practice Greenhealth, 2018) and Global Green and Healthy Hospitals (Global Green and Healthy Hospitals, 2017) of Healthcare Without Harm offer healthcare-specific environmental reporting, largely around facilities operations. These instruments offer potential opportunities for future development of comprehensive environmental data collection from hospitals and health systems. Corporate social responsibility reporting structures, as discussed above, may serve as alternatives; however, these are not healthcare-specific.

The Choosing Wisely (American Board of Internal Medicine Foundation, 2018) initiative has partnered with medical, nursing, and dental specialty societies in several countries to develop specific evidence-based recommendations regarding the appropriate use of healthcare resources and elimination of harm due to over-investigation and over-treatment. The Getting It Right the First Time (NHS Royal, 2020) program in the United Kingdom is an analogous organization dedicated to improving quality within the National Health Service specifically as it relates to unnecessary and inefficient care. The Wise List (Stockholm County, 2015; Eriksen et al., 2018) initiative in Sweden, developed by the Stockholm County Council, is an essential medicines formulary for prescribers that incorporates the "PBT" index (persistence, bioaccumulation, and toxicity) to guide environmentally preferable prescribing. Such initiatives provide opportunity to mainstream environmental stewardship into the healthcare quality discourse by capitalizing on the existing specialty-specific recommendations framework to solicit and disseminate best practices that incorporate environmental performance.

Various aspects of sustainable clinical care are particularly appealing to patients. Examples include green architecture with daylighting and green spaces, streamlined care pathways, and reassurance that the impact of their healthcare activities on the environment is minimized (Brambilla et al., 2019; Ulrich et al., 2008; Sadler et al., 2009). Similarly, evidence suggests that environmental sustainability initiatives in organizations promote higher levels of staff engagement, lower attrition rates, and increased workplace satisfaction (Ulrich et al., 2008; Limited EYG, 2020). In order to capture these important psychosocial and organizational impacts (Tudor et al., 2007; Schenk et al., 2016), a qualitative research agenda could incorporate patient and staff preferences, to complement quantitative initiatives.

4.2. *Infection control and pollution prevention*

Many of the standards governing the delivery of health services impede the implementation of environmentally sustainable practices. Thus, regulators and oversight bodies are key stakeholders requiring engagement, with the aim of deriving evidence-based standards that seek to optimize both patient care and environmental performance. For example, the American Society of Heating, Refrigerating and Air-Conditioning Engineers sets standards for heating, ventilation and air-conditioning (HVAC) of clinical spaces (American Society of Heating RaA-CE, 2017). Meeting or exceeding these standards is highly energy-intensive, without clear evidence that correlates air exchange rates with bacterial loads and infection rates (Mousavi et al., 2019). HVAC setbacks represent one promising opportunity for financial and environmental savings (Sheppy et al., 2014).

Infection control is of paramount concern for the healthcare industry to keep patients safe and reduce costs. Preventing healthcare-acquired infections is also important to conserve natural resources and prevent pollution through avoidance of otherwise unnecessary clinical care. Excessive infection control practices, however, are a major driver of avoidable pollution and wasted resources. Many infection control policies and procedures are empirically implemented without evidence of significant risk reduction, noticeably increasing the uptake of single-use medical devices and supplies in healthcare (Sherman and Hopf, 2018; Daschner, 1991; Daschner and Dettenkofer, 1997).

A common infection control viewpoint assumes there is no limit to the cost or materials required to avoid *any* risk of healthcare acquired infection. However, financial resources and raw materials are finite, and healthcare generates pollution that indirectly harms human health. While infection prevention is essential, non-evidence-based standards and unscrutinized practices drive excessive behaviors that are causing preventable indirect harm to society that can no longer be neglected (Sherman et al., 2018; Sarfaty et al., 2016). Finding the right balance between infection control practices and pollution prevention requires systematic risk stratification (Sherman and Hopf, 2018). Collaboration between sustainability experts and infection control experts, such as those from the Society for Healthcare Epidemiology in America and other health professional societies, will be required to develop expert guidelines that incorporate environmental health criteria. Further engagement will be required with healthcare regulators such as the Center for Disease Control, the Food and Drug Administration, and local departments of public health, as well as the Joint Commission and other oversight bodies to ensure integration of sustainability safety standards.

4.3. Quality, safety and value

It has been nearly 20 years since the Institute of Medicine released its landmark report, *To Err is Human*, catapulting the issue of medical errors to the forefront of public consciousness. The result has been an era of patient safety and quality improvement that has given rise to novel fields of study, complex quality measurement and reporting mechanisms such as those described above, and now remuneration structures centered around patient outcomes. The present generation of clinicians has been indoctrinated into the quality and safety paradigm and is fluent in this parlance. More recently, attention has shifted to value-based healthcare reform, as both public and private systems struggle to meet increasing demands and contain costs. The environmental sustainability agenda for healthcare shares the fundamental principles of these paradigms, as human health damages from healthcare pollution are an issue of patient safety and quality, and eliminating waste and inefficiency from healthcare systems is a mainstay of improving healthcare value.

Integrating environmental sustainability into quality- and value-based healthcare reform, and communicating in the language of these paradigms, can help to achieve rapid uptake and durability of healthcare sustainability initiatives. This strategic approach includes developing cost-effectiveness methodologies that incorporate environmental and human health damages of healthcare activities, and advocating for full-cost accounting (internalizing previously externalized pollution-related healthcare costs), in all healthcare decision-making. Value is traditionally viewed through the lens of the “Triple Aim of Healthcare”: the best patient health outcomes for the most people at the least cost (The IHI Triple Aim Initiative, 2020). Expanding on this framework, a broader viewpoint further integrates public health and well-being impacts of those affected by the healthcare industry up and down the supply chain (Mortimer et al., 2018a, 2018b; United Nationals Global Compact, 2018; Ethical Trading Initiative, 2018):

$$Value = \frac{\text{Outcomes for Patients} + \text{Populations}}{\text{Environmental} + \text{Social} + \text{Financial costs}}$$

Framing sustainability initiatives in terms of quality and value improvement resonates with administrators, clinicians and policy makers. This is consistent with the “Health in all Policies” (American Public Health, 2018) public health principle, and an expanded view of the duty to “first, do no harm.” Such language has already begun to be embedded into the United Kingdom National Institute for Health and Care Excellence (National Institute for Health and Care, 2017). Other leading healthcare quality and safety organizations such as the Institute for Healthcare Improvement (The IHI Triple Aim Initiative, 2020) and the Anesthesia Patient Safety Foundation (Anesthesia Patient Safety, 2020) can integrate this framework and advance a synergistic agenda around resource stewardship, safety and quality.

5. Education: Communicating clinical sustainability

For many health professionals, the leading barrier to workplace-based environmental stewardship is a lack of knowledge and skills (Sarfaty et al., 2016; Sarfaty et al., 2014a, 2014b; Thiel et al., 2017). Continuing education and quality improvement project requirements in the area of clinical sustainability (Mortimer et al., 2018a, 2018b) are driving specialty-specific post-graduate education opportunities through professional societies. The Institute for Health Care Improvement Open School (Institute for Healthcare Improvement, 2018) can build core skills in healthcare improvement, safety, system design, and leadership, and is well-suited for integration of educational opportunities in sustainable healthcare.

To prepare the future healthcare workforce, educators are integrating core learning objectives for planetary health and healthcare sustainability science into pre-clinical and clinical training (Zuegge et al., 2019; Walpole and Mortimer, 2017) and fostering the notion of environmental stewardship as a core professional responsibility (Thompson et al., 2014; Teherani et al., 2017; Wellbury et al., 2016; Sherman, 2016; Barna and Vyas, 2015; Barna et al., 2015; Bland et al., 2000; Butterfield et al., 2014; Pearson and Barna, 2015; Walpole et al., 2019; The Lancet, 2020). Steps are also underway to set training mandates to close the education gap (Environment and Health, 2017). Health-themed content for students in engineering and other environmental sciences could foster the development of a collaborative sustainable healthcare specialization.

6. Conclusion: The future of sustainable clinical care

5.1. Re-thinking and Re-design

Currently, healthcare pollution is causing indirect public health damages and increasing healthcare service needs. A transformational vision is required to achieve a sustainable healthcare system and reach ambitious targets such as those set forth by the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, 2018) and the UN SDGs (United Nations, 2020) within the short time horizon mandated by the urgency of global environmental change.

Optimizing resource and waste management practices are necessary components of healthcare sustainability; however, these are insufficient to achieve a sustainable future. Minimizing the environmental impact of healthcare activities requires innovation beyond determination of environmentally preferable alternatives, or ‘the least bad choice.’ The best metrics are designed not to measure and reinforce the status quo, but rather to influence policies, investment and management decisions, and design choices toward a better system. Innovation should aim to achieve superior outcomes while preventing undesirable consequences. This “first principle” of design envisions enhanced performance while eliminating toxicity, hazards, and waste. Rethinking all aspects of healthcare delivery is required (Zimmerman et al., 2020).

Prevention is widely recognized to be the most effective means of ensuring healthcare sustainability from environmental, social, and economic standpoints, but requires a paradigm shift away from a system focused on the treatment of illness to one dedicated to promoting health. This requires policies that support primary care and public health, robust screening programs, fair and universal access to healthcare resources, as well as funding models that align incentives with wellness outcomes. Addressing the broader social determinants of health necessitates an acknowledgement of the impact of economic disparities on health, as well as the intersection of healthcare with other fields such as food systems, urban design, and transportation, and the need for cross-sectoral collaboration.

To date, framing environmental sustainability in terms of its co-benefits for the healthcare system and population health has been an effective strategy for introducing this agenda as non-threatening to core healthcare mandates and by emphasizing compatibility with current resource constraints. However, achieving the ambitious targets that are necessary to mitigate dangerous environmental instability requires that healthcare sustainability be recognized as imperative to the health of current and future populations, and to the viability of health systems. Aligning and integrating this agenda with the widely accepted core values of quality, safety and high-value care is the necessary next step toward a sustainable future.

5.2. Next steps: Formation of a global commission on environmental sustainability in healthcare

To further research and implementation science, formation of a formal Commission on Environmental Sustainability in Healthcare is required (Table 1) (Sherman et al., 2019). Such an endeavor will require strategic institutional partnerships, and dedicated financial and human resources (Yamey et al., 2018). The objective of mainstreaming environmental performance and shepherding the transformation to a sustainable healthcare system is ambitious, yet within the realm of the imagination. The alternative future is unacceptable.

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