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Robotic surgery and environmental sustainability: from challenge to opportunity

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INTRODUCTION

Sustainability has emerged as one of the greatest challenges facing modern healthcare[1]. It encompasses three inseparable dimensions - environmental, economic and social. In surgery, the economic cost of innovation shapes equitable access to care, while its environmental footprint increasingly affects the resilience of healthcare systems. As surgical innovation accelerates, its value can no longer be judged solely by clinical outcomes and cost: environmental sustainability has become a third pillar in the evaluation of new surgical technologies.

Healthcare itself has a substantial environmental footprint. If healthcare were a country, it would rank as the world's fifth largest emitter of greenhouse gases, accounting for approximately 5% of global emissions[2]. Within hospitals, operating rooms are among the most resource-intensive environments, generating an estimated 20%-30% of hospital waste while consuming three to six times more energy than other departments[3]. Surgery therefore bears a particular responsibility to reduce healthcare’s environmental impact and should treat sustainability as a core component of quality improvement.

Robotic surgery exemplifies this challenge. Over two decades it has transformed minimally invasive surgery, and its adoption continues to accelerate worldwide as clinical evidence expands across specialties and healthcare systems invest heavily in the technology. In England, the National Health Service has set a target that 90% of minimally invasive procedures be robot-assisted by 2035[4]. As robotic surgery becomes integral to modern care, understanding and minimizing its environmental impact is no longer optional - particularly as climate change ceases to be a distant threat. Recent heatwaves across Europe are a reminder that the consequences of greenhouse gas emissions are already affecting our societies and our healthcare systems.

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The question is therefore no longer whether robotic surgery improves patient outcomes, but whether those benefits can be delivered more sustainably. Rather than asking whether robotic surgery is compatible with environmental sustainability, we should ask how it can itself become more sustainable while preserving its clinical advantages.

THE ENVIRONMENTAL FOOTPRINT OF ROBOTIC SURGERY: WHERE DOES IT REALLY COME FROM?

When the environmental impact of robotic surgery is discussed, attention often focuses on intraoperative electricity consumption. Yet life-cycle assessments consistently show that electricity accounts for only a small fraction of the overall footprint[5,6]. Most greenhouse gas emissions arise across the life cycle of the technology: manufacture of the robotic system, production of instruments, packaging, transportation, sterilization and end-of-life management[5-7]. The robotic platform itself, as a complex piece of capital equipment, is a major contributor to this burden. Environmental performance should therefore be evaluated across the entire life cycle, making life-cycle assessment the most comprehensive framework for quantifying the environmental impact of surgical innovation[5,6].

WHAT DOES THE EVIDENCE ACTUALLY TELL US?

Most published life-cycle assessments report a greater environmental impact for robotic surgery than for conventional laparoscopy, driven by additional capital equipment, greater material requirements and the use of disposable or limited-reuse instruments[5,6]. This evidence has recently been strengthened by a life-cycle assessment of hepatectomy, which demonstrated that robotic liver surgery generated a substantially greater carbon footprint than conventional laparoscopic surgery and approximately 1.5-fold higher emissions than open surgery[8].

These findings warrant caution. Studies differ considerably in methodology, system boundaries and assumptions, making direct comparison difficult[5,6], and environmental performance is highly context-dependent - shaped by procedural complexity, institutional organization and, above all, robot utilization. Rather than showing robotic surgery to be inherently unsustainable, current evidence suggests its impact depends largely on how robotic programs are implemented.

Importantly, existing studies mostly evaluate the procedure itself and rarely capture downstream effects across the patient's care pathway[5,6]. Future work should move beyond procedure-level analysis to integrate downstream outcomes and provide a more comprehensive assessment. In selected patients, curative surgery may avoid prolonged systemic therapies, including chemotherapy or targeted treatments, which themselves require resource-intensive development, manufacturing, transport, and administration. Artificial intelligence (AI)-driven precision medicine could further support this approach by identifying patients most likely to be cured by surgery alone, thereby maximizing both clinical benefit and environmental sustainability[9].

CAN ROBOTIC SURGERY BECOME PART OF THE SOLUTION?

Despite its current burden, robotic surgery should not be seen solely as part of the problem; it may also become part of the solution by improving both patient outcomes and the organization of surgical care.

Its clinical benefits may indirectly reduce environmental impact by shortening hospital stay and accelerating recovery, thereby lowering resource use. These benefits are best documented in urology[10] and are most likely in selected complex digestive procedures, particularly rectal cancer and other technically demanding pelvic operations[11]. Although a consistent reduction in complications has yet to be demonstrated, even modest gains in recovery may translate into meaningful environmental benefit by reducing prolonged hospitalization, reoperations and additional treatments.

The greatest opportunity, however, lies in the organizational change robotic surgery drives. Because platforms require substantial investment, they naturally encourage centralization, specialization and high-volume programs - improving not only clinical outcomes but also resource efficiency by maximizing platform utilization and avoiding duplication of expensive equipment. Sustainability thus depends less on the robot than on how robotic surgery is organized and delivered.

UTILIZATION IS PROBABLY THE MOST IMPORTANT DETERMINANT OF SUSTAINABILITY

Utilization is probably the single most important determinant of the environmental footprint of robotic surgery[5,6]. Because manufacturing a system represents a substantial environmental investment, increasing procedural volume progressively dilutes that capital cost across individual operations; the carbon footprint of a platform therefore depends less on the robot than on how intensively it is used over its lifetime.

This also explains apparently conflicting conclusions. Some studies identify the platform as the principal emissions source, while others find disposable instruments dominant once volume rises. Rather than contradictory, these findings underline the role of utilization, procedure mix and institutional organization.

The practical implications are considerable. More than 3.2 million robotic procedures were performed worldwide in 2025, yet the average da Vinci system still performs only around 270 annually[12]. Raising utilization through centralized, high-volume programs - potentially exceeding 500 procedures per platform per year - would improve economic efficiency and substantially reduce the environmental impact per procedure by spreading the carbon cost of manufacturing across many more patients. Improving sustainability therefore does not require fewer robotic systems, but better use of those already available.

MAKING ROBOTIC SURGERY MORE SUSTAINABLE: A SHARED RESPONSIBILITY

Making robotic surgery more sustainable will require action from surgeons, institutions and industry, and most effective interventions are already available, relying on changes in practice rather than technological breakthroughs.

Surgeons can make an immediate difference by rationalizing surgical trays, standardizing techniques and instrument sets, and avoiding the routine opening of instruments that go unused. Better waste segregation, minimizing packaging and more judicious selection of disposable devices further reduce both environmental impact and disposal costs[13,14]. Sustainability should become another dimension of surgical quality, alongside safety, efficiency and clinical outcomes.

Institutions also have a crucial role. Robotic programs should be developed only where sufficient procedural volume can be achieved, allowing expensive systems to be fully used while supporting specialized, high-volume teams; from both economic and environmental perspectives, low-volume programs are difficult to justify. Hospitals should also incorporate environmental indicators - carbon footprint monitoring and standardized reporting - into quality improvement.

Technology should be matched to procedural complexity. Not every operation requires a full multi-arm platform. For selected lower-complexity procedures, lighter robotic systems or collaborative devices (cobots), such as camera-holding platforms, may deliver many of the advantages of robotic assistance while substantially reducing equipment requirements. Choosing the appropriate level of robotic assistance is itself an important component of sustainable surgical innovation.

Finally, industry will be decisive. Designing systems on circular-economy principles, increasing instrument longevity, reducing packaging and providing transparent life-cycle assessments should become standard practice. Encouraging initiatives have already emerged: Intuitive's Xi-R reconditioning program extends platform lifespan, and the maximum permitted instrument uses have risen from 10 to 18[12], reducing capital- and instrument-related impact. Beyond robotics, Ethicon's recycling program shows that circular strategies are feasible in surgical practice[14]. Together with evidence that hybrid reusable/single-use instruments can reduce procedure-related carbon emissions by approximately 75% compared with fully disposable instruments[13], these examples show that sustainability can evolve alongside innovation.

CAN ARTIFICIAL INTELLIGENCE MAKE ROBOTIC SURGERY GREENER?

At present, there is no evidence that AI directly reduces the environmental footprint of robotic surgery. If utilization is a key determinant of that footprint, AI is best understood as an enabling technology that can improve the sustainability of robotic surgery through several complementary mechanisms. Machine-learning approaches to operating-room management predict case duration more accurately than conventional scheduling[15,16], enabling tighter lists and reducing both under- and over-use of theatre time; randomized evidence has already shown gains in scheduling accuracy, waiting times and resource utilization[17].

Applied to robotic surgery, algorithms integrating case complexity, team availability, turnover and sterilization cycles could substantially raise annual throughput - an organizational challenge precisely suited to AI. Rather than changing the technology, AI could improve sustainability by distributing the carbon cost of manufacturing across many more procedures. Beyond operating-room scheduling, AI may also reduce the environmental footprint of robotic surgery by improving operative efficiency itself. AI-assisted preoperative planning, surgical simulation, and intraoperative navigation have the potential to streamline complex procedures, facilitate surgical decision-making, and shorten operative duration. Because electricity consumption increases with operating time, reducing procedure length may indirectly decrease the carbon footprint of robotic surgery. More efficient procedures may also reduce unnecessary instrument exchanges and disposable resource utilization, although this potential benefit remains to be demonstrated. Although robust evidence demonstrating this environmental benefit is still lacking, these applications represent promising avenues through which AI could contribute to more sustainable robotic surgical practice.

Beyond improving operative efficiency, AI may also contribute to sustainability through more appropriate patient selection. As highlighted by Aldoori *et al.*, avoiding unnecessary surgical procedures represents an important strategy for reducing the environmental impact of surgical care[9]. AI-driven precision medicine may help identify patients who are unlikely to benefit from surgery because of a high risk of early recurrence or postoperative complications. Likewise, AI-assisted decision support could facilitate selection of the most appropriate surgical approach for each patient, reserving robotic surgery for cases in which its clinical advantages are expected to outweigh its environmental cost. Such optimization of patient selection could ultimately contribute to reducing the overall carbon footprint of surgical care.

Beyond scheduling and decision support, AI could make environmental performance measurable in routine practice. Automated capture of instrument use, tray composition, disposable consumption and energy use would let hospitals generate procedure-level carbon and waste metrics without the labor-intensive audits that currently confine life-cycle assessment to research settings. Computer vision could further standardize operative workflow and instrument selection, reducing unnecessary variation and waste[18].

These applications remain largely prospective. Importantly, AI itself is associated with substantial computational requirements, electricity consumption, and carbon emissions related to model development, deployment, and data-center infrastructure, which are rarely included in healthcare carbon accounting and should not be overlooked[19]. Nevertheless, modeling studies suggest that AI-enabled optimization of care pathways could substantially reduce healthcare-related emissions overall[20]. The overall environmental benefit of AI will therefore depend on whether these system-level gains outweigh the environmental costs associated with AI infrastructure. In robotic surgery, AI is likely to contribute to sustainability not by changing the technology itself, but by helping healthcare systems organize, measure, and deploy it more efficiently.

CONCLUSION

Robotic surgery represents one of the greatest opportunities - and challenges - for the sustainability of modern surgical care. Although current life-cycle assessments generally report a greater footprint than conventional laparoscopy, this is not intrinsic to the technology but largely reflects how robotic surgery is organized, implemented and utilized.

Making it more sustainable will depend less on limiting innovation than on directing it wisely: better utilization, centralized high-volume programs, reusable instruments, circular-economy principles and more thoughtful implementation all offer tangible ways to reduce environmental impact while preserving clinical benefit.

Ultimately, sustainability should become another benchmark of surgical quality, alongside safety, effectiveness and patient outcomes. The future of robotic surgery will be measured not only by what robots can do for patients, but by how responsibly we choose to use them.

DECLARATIONS

Authors' contributions

The author contributed solely to the article.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool ChatGPT (version 5.5, released 2026-08-07) was used solely for language editing, stylistic refinement, and improvement of manuscript readability. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. The author takes full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

Tranchart H is an Editorial Board Member of the journal *Artificial Intelligence Surgery*. Tranchart H was not involved in any steps of the editorial process, including reviewer selection, manuscript handling, or decision-making.

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Not applicable.

Consent for publication

Not applicable.

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