Review article

Is there a place for robotic surgery in modern thoracic oncosurgery?

Michał Grabysa[1], Łukasz Klepacki[1, 2], Grzegorz Kulesza[1]

[1] *Department of Thoracic Surgery, The Center for Pulmonary Diseases, Olsztyn, Poland*

[2] *Department of Anatomy, University of Warmia and Mazury, Olsztyn, Poland*

ABSTRACT

Robotic-assisted thoracic surgery (RATS) has transformed the management of thoracic oncologic diseases, including lung cancer, mediastinal tumors, and esophageal cancer, by offering precision, reduced invasiveness, and enhanced visualization compared to open thoracotomy and video-assisted thoracoscopic surgery (VATS). This review evaluates RATS' current role and future potential, analyzing oncologic efficacy, clinical outcomes, and economic implications. RATS demonstrates shorter hospital stays, lower complication rates and survival rates equivalent to traditional methods.

Despite challenges such as high costs and steep learning curves, technological advancements – artificial intelligence (AI), single-port systems, and haptic feedback – promise to expand its utility.

Drawing on literature from 2015 to 2025, this paper affirms RATS' vital place in modern thoracic surgery, particularly in thoracic oncology, with its role poised to grow as economic and training barriers are overcome. The future of RATS depends on innovation and accessibility, which could lead to changes in the standards of care in the coming years.

Key words: robotic surgery, thoracic surgery, thoracic oncology, lung cancer, cost-effectiveness, future innovations

Correspondence:
Michal Grabysa, MD
Department of Thoracic Surgery,
The Center for Pulmonary Diseases, Olsztyn, Poland
10-357 Olsztyn, ul. Jagiellońska 78
e-mail: michalgrabysa@gmail.com

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INTRODUCTION

Thoracic surgery has undergone a remarkable transformation over the past century, driven by the dual goals of minimizing patient trauma and maximizing therapeutic efficacy. In the early 20th century, open thoracotomy was the standard approach, requiring large incisions (15–20 cm), rib spreading, and extended recovery periods (8–12 weeks), with complication rates often exceeding 30–40%. This invasive method, while effective for accessing the lungs, mediastinum, and esophagus, imposed significant physical burdens on patients, particularly those with malignancies requiring subsequent adjuvant therapies. The introduction of video-assisted thoracoscopic surgery (VATS) in the 1990s marked a revolutionary shift, reducing incision sizes to 3–5 cm, blood loss to 200–300 mL (vs. 500–1,000 mL for open surgery), and hospital stays to 5–7 days. VATS quickly became the minimally invasive gold standard, especially for early-stage lung cancer and benign thoracic conditions, due to its balance of efficacy and reduced morbidity.

However, VATS has inherent limitations: 2D imaging restricts depth perception, rigid instruments limit maneuverability in the confined thoracic cavity, and prolonged procedures cause ergonomic strain for surgeons. These shortcomings spurred the development of robotic-assisted thoracic surgery (RATS), introduced in the early 2000s with the da Vinci Surgical System. RATS offers 3D high-definition visualization (10× magnification), articulated instruments with 7 degrees of freedom, and tremor filtration, providing surgeons with enhanced precision and control. Since its inception, RATS has gained traction, particularly in thoracic oncology, where procedures like pulmonary lobectomy, thymectomy, and esophagectomy demand meticulous dissection near critical structures – heart, lungs, and great vessels. RATS is expected to account for more than 20% of lobectomy procedures in high-volume centers, reflecting the growing acceptance of this method [1].

Despite promising results, the role of RATS in modern thoracic surgery remains controversial. Proponents laud its ability to improve oncologic outcomes – such as higher lymph node yields, and equivalent survival rates – while reducing postoperative pain and hospital stays. Critics, however, highlight substantial economic barriers, with system acquisition costs ranging from €920,000 to €1,840,000 and per-case expenses of €2,760–€4,600, far exceeding VATS (€1,840–€2,760) [2]. Additionally, the paucity of long-term randomized controlled trials (RCTs) comparing RATS to VATS or open surgery fuels skepticism about its superiority. This review seeks to address these debates by synthesizing evidence from 2015 to 2025, with a focus on RATS current contributions and future potential in thoracic oncology. We explore its technical advantages, clinical efficacy, economic challenges, and emerging innovations, asking: does RATS have a lasting place in thoracic surgery, and how might it shape the future of cancer treatment in this field?

METHODOLOGY

This review integrates peer-reviewed studies published between 2015 and 2025, sourced from PubMed, Scopus, Web of Science, and proceedings of major thoracic surgery conferences (e.g., European Society of Thoracic Surgeons). Search terms included "robotic-assisted thoracic surgery", "RATS vs. VATS", "robotic lobectomy outcomes", "mediastinal robotic surgery", "robotic esophagectomy" and "thoracic oncology robotics". The inclusion criteria prioritized studies reporting oncologic endpoints (e.g., R0 resection rates, lymph node yield, survival), clinical outcomes (e.g., morbidity, length of stay), and economic analyses (e.g., costs in €), with a preference for randomized controlled trials (RCTs), large cohort studies (>100 patients), systematic reviews, and meta-analyses. 30 references were selected that reflect the state of practice as of 2025, thereby providing a reference to current robotic platforms such as the da Vinci Xi.

Studies lacking comparative data, predating 2015, or without clear oncologic or clinical endpoints were excluded to maintain focus on modern technology and practice. Data were qualitatively synthesized, with quantitative metrics – such as odds ratios, hazard ratios, and p-values – extracted where available to support statistical rigor. Subgroup analyses focused on lung cancer resection, mediastinal tumor management, esophageal cancer surgery, and emerging oncologic applications, with additional attention to surgeon training requirements, cost-effectiveness, and technological advancements. This methodology provides a comprehensive foundation for evaluating RATS role and future trajectory in thoracic oncology, grounded in contemporary evidence.

HISTORICAL CONTEXT AND EVOLUTION OF THORACIC SURGERY

The evolution of thoracic surgery mirrors broader advances in surgical science, transitioning from crude, invasive techniques to sophisticated, minimally invasive approaches. In the early 20th century, open thoracotomy dominated, requiring extensive incisions and rib retraction to access the thoracic cavity. While effective for resecting lung tumors or managing mediastinal masses, it carried high morbidity – 30–40% complication rates, including infection and respiratory failure – and prolonged recovery (8–12 weeks). The advent of video-assisted thoracoscopic surgery (VATS) in 1991, pioneered by surgeons like Rodney Landreneau and Michael Mack from University of Pittsburgh, USA, revolutionized the field of modern throracic surgery. VATS reduced incision sizes to 3–5 cm, blood loss to 200–300 mL (vs. 500–1,000 mL for thoracotomy), and hospital stays to 5–7 days, establishing it as the minimally invasive standard by the late 1990s, particularly for early-stage lung cancer and benign conditions.

Despite its success, VATS limitations – flat imaging, restricted instrument mobility, and surgeon fatigue – prompted the exploration of robotic surgery. The da Vinci Surgical System, approved by the FDA in 2000, debuted in thoracic surgery with procedures like thymectomies and lobectomies. Early adopters reported feasibility but faced challenges: operative times averaged 200–300 min, costs were substantial (initial systems: €920,000–€1,840,000), and surgeon inexperience led to inconsistent outcomes [3]. By 2015, technological upgrades – such as the da Vinci Xi's improved docking, enhanced 3D imaging, and streamlined instrumentation – along with growing expertise, narrowed these gaps. RATS ability to navigate the thoracic cavity's anatomical complexity – tight spaces near the heart, lungs, and great vessels – made it particularly suited for oncologic surgery, where precision in resection and lymphadenectomy is critical.

By 2025, RATS has evolved from a niche technology to a mainstream contender, with over 20% of lobectomies performed robotically in specialized centers [1]. This growth reflects its alignment with thoracic surgery's historical trajectory toward reduced invasiveness and improved outcomes, setting the stage for its current and future role in managing oncologic diseases. The transition from thoracotomy to VATS to RATS underscores a relentless pursuit of innovation, with each step building on the last to address the unique challenges of thoracic pathology.

ROLE AND FUTURE OF ROBOTIC SURGERY IN THE THORACIC ONCOLOGY

RATS has emerged as a transformative technology in the treatment of thoracic oncologic diseases, offering unmatched precision, enhanced 3D visualization, and ergonomic advantages over open thoracotomy and VATS. Current role of RATS is most pronounced in lung cancer resection, mediastinal tumor excision (notably thymomas), and esophageal cancer surgery – malignancies where complete resection (R0), lymph node harvest, and long-term survival are critical endpoints. Beyond its established applications, RATS holds significant promise for the future, driven by technological advancements such as artificial intelligence (AI), single-port systems, and haptic feedback, which could further elevate oncologic outcomes. This section explores RATS' present contributions and future potential in thoracic oncology, synthesizing technical benefits, clinical data, and emerging trends from 2015 to 2025.

ROBOTIC SURGERY IN LUNG CANCER RESECTION

Lung cancer, predominantly non-small cell lung cancer (NSCLC), is the most prevalent thoracic malignancy, with pulmonary resection – lobectomy, segmentectomy, or pneumonectomy – serving as the cornerstone of curative treatment for stages I–IIIA. RATS has solidified its role in this domain, matching or surpassing VATS and open surgery in oncologic efficacy while reducing perioperative morbidity, with future innovations poised to enhance its impact.

RATS leverages the da Vinci Surgical System's 3D imaging (10× magnification) and wristed instruments with 7 degrees of freedom, exceeding VATS' rigid tools and open surgery's manual constraints. A standard robotic lobectomy uses a 3- to 4-port approach: a camera port (8–12 mm) in the 7th intercostal space along the midaxillary line, 2 working ports (8 mm) in the 5th and 9th spaces, and an assistant port (12 mm) in the 8th space posteriorly for stapling and specimen retrieval. This setup enables precise dissection of hilar structures – pulmonary artery, vein, and bronchus – ensuring R0 resection with minimal trauma. Mediastinal lymph node dissection, vital for staging, benefits from RATS' ability to access stations 2R, 4R, 7, and 10, improving nodal clearance over VATS [4]. Tremor filtration and the ergonomic console enhance accuracy, reducing risks like vascular injury in complex cases.

The results of numerous clinical studies confirm the effectiveness of RATS in the surgical treatment of lung cancer. Yang et al. [5] reported R0 resection rates of 98% in 250 robotic lobectomies, comparable to VATS (97%, $p = 0.67$), with higher lymph node yields (median 14 vs. 10; $p < 0.001$), enhancing staging accuracy and reducing understaging risks (e.g., occult N1/N2 disease). Zirafa et al. [6] found 5-year disease-free survival (DFS) of 82% and overall survival (OS) of 80% in 300 patients, aligning with VATS (DFS 80%, OS 78%) and open surgery (DFS 79%, OS 79%). A noteworthy 2023 meta-analysis by Zhang et al. [7], including 4,000 patients in 15 studies, confirmed no significant difference in 5-year OS (HR = 0.95; 95% CI: 0.88–1.03; $p = 0.41$), with a trend towards a lower risk of relapse in RATS (12% vs. 15%; $p = 0.09$). Perioperative benefits include shorter hospital stays (4 days vs. 6 days for VATS; $p < 0.01$), reduced pain (VAS 2 vs. 4; $p = 0.03$), and less blood loss (100 mL vs. 150 mL; $p = 0.02$), expediting adjuvant therapy [5]. Complications like pneumonia (10% vs. 18%; $p < 0.05$) and atrial fibrillation (12% vs. 20%; $p < 0.05$) were also lower in patients treated with RATS [8].

It seems that RATS is ideal for early-stage NSCLC (T1–T2, N0–N1), obese patients (BMI >30 kg/m^2), and those with central tumors

or prior surgery, where its precision overcomes VATS limitations. Contraindications include T4 tumors, severe pulmonary dysfunction (FEV_1 <30%), or emergencies due to setup times (20–30 min). Challenges include longer operative times (180–240 min vs. 150–200 min for VATS), increasing anesthesia exposure and costs – system acquisition at €920,000–€1,840,000 and per-case expenses of €2,760–€4,600 versus €1,840–€2,760 for VATS [2, 9].
Dynamically developing new information technologies promise to strengthen the role of RATS in the modern approach to lung cancer surgery. AI-driven navigation could optimize resection margins and nodal sampling, while single-port systems may reduce incisions, enhancing recovery [10, 11]. The coming years hold promise for improvements in real-time tumor margin detection that may further improve R0 rates, solidifying RATS as the standard of care in lung cancer surgery [12].

ROBOTIC SURGERY IN MEDIASTINAL TUMOR RESECTION

Mediastinal tumors, especially thymomas, are a key oncologic focus due to their malignant potential and paraneoplastic associations (e.g., myasthenia gravis). RATS has established a significant role here, with future advancements poised to expand its utility [13].
Robotic thymectomy typically employs a 3-port approach from the left chest: a camera port (8 mm) in the 5th intercostal space along the anterior axillary line, and working ports (8 mm) in the 3rd and 7th spaces. The 3D visualization and endowrist instruments enable en bloc resection of thymic tissue and fat, ensuring complete tumor removal while preserving phrenic nerves and great vessels. For tumors >5 cm, an assistant port (12 mm) aids specimen extraction without compromising margins. Compared to sternotomy's large incisions (8–10% nerve injury risk) or VATS' 2D limitations, RATS minimizes trauma and enhances precision [13].
Marulli et al. [13] reported R0 resection in 96% of 250 thymoma cases, matching sternotomy (95%; p = 0.78), with lower morbidity. 5-year OS for stage I–II thymomas was 90%, with recurrence rates of 5% versus 7% for VATS (p = 0.35). Blood loss was 50 mL versus 150 mL for sternotomy (p <0.001), and hospital stays averaged 3 days versus 7 days (p <0.01). Phrenic nerve preservation succeeded in 98% of cases versus 92% for VATS (p = 0.04), reducing respiratory issues [14]. For other malignancies (e.g., germ cell, neurogenic tumors), RATS achieves R0 rates of 97% versus 94% for VATS (p = 0.12) and lowers nerve injury (3% vs. 8%; p = 0.03). Reduced pain (VAS 3 vs. 5; p = 0.04) and faster recovery (10 days vs. 14 days; p = 0.03) support adjuvant therapy optimal timing [15].
When considering appropriate patient qualification, the RATS method is appropriate for stage I–II thymomas (<5 cm) and benign tumors, whereas for stage III–IV tumors or >10 cm with vascular invasion, open surgery is recommended. The costs (€2,760–€3,680 per case compared to €1,380–€1,840 for VATS) and longer operative time (150 min compared to 120 min) are a barrier, which limits the wide availability of the method [16].
Dynamic RATS development, especially in the field of haptic feedback, approaching clinical applications, may improve nerve preservation, while artificial intelligence may influence the extent of resection, reducing the risk of tumor recurrence [17]. In turn, miniaturization of systems may extend RATS to smaller or pediatric tumors, broadening its oncological scope [12].

ROBOTIC SURGERY IN ESOPHAGEAL CANCER

Esophageal cancer, including adenocarcinoma and squamous cell carcinoma, requires extensive resection and lymphadenectomy. RATS is playing an increasingly important role in these difficult cases, and future innovations will certainly strengthen its role in modern thoracic oncology.
Robotic esophagectomy (e.g., Ivor Lewis, McKeown) uses 4 thoracic ports: a camera port (8 mm) in the 8th intercostal space, 2 working ports (8 mm) in the 6th and 10th spaces, and an assistant port (12 mm). The 3D view and articulated instruments excel in dissecting the esophagus from the trachea, aorta, and pericardium, and in lymphadenectomy along the recurrent laryngeal nerve and thoracic duct. Precision in anastomosis reduces leak risks, aiding adjuvant therapy timing [18].
Wang et al. [19] reported R0 resection in 94% of 200 cases versus 90% for VATS (p = 0.10), with higher lymph node yields (median 22 vs. 18; p = 0.02), improving staging (15% N0 to N1 upstaging). 5-year OS was 60% versus 58% for VATS (p = 0.35), with fewer leaks (5% vs. 20%; p <0.01). Hospital stays averaged 7 days versus 9 days (p = 0.04).
Analyzing the data available in the literature, it seems that RATS is the optimal solution for T1–T3, N0–N1 tumors, whereas in the case of T4 or highly advanced N2–N3 tumors, open surgery is recommended. Unfortunately, the longer operative time (300–400 min vs. 250–300 min for VATS) and costs (€2,760–€4,600 per case) limit the wider use of the method [9].
Single-port systems and autonomous suturing could reduce risk of anastomotic leakage and operative times, while AI support may enhance nodal mapping, improving survival [10, 12].

Emerging oncologic applications

RATS is expanding to chest wall tumors (R0 rates via en bloc resection), pulmonary metastasectomy (95% R0 rates), and pediatric tumors (e.g., neuroblastoma), with future miniaturized systems and AI enhancing precision [1, 12, 14].

RATS currently enhances thoracic oncology with superior resection, nodal harvest, and recovery, matching or exceeding VATS and open surgery. Costs and training needs temper its reach, but future advancements – AI, single-port systems, haptic feedback – promise to redefine oncologic standards in the following years.

SUMMARY OF THE BENEFITS OF ROBOTIC THORACIC SURGERY

RATS offers distinct advantages over VATS and open surgery, particularly in thoracic oncology:

- **Precision and visualization:** The 3D high-definition imaging (10× magnification) and articulated instruments provide unparalleled accuracy, critical for dissecting near vital structures. This enhances R0 resection rates (e.g., 98% in lung cancer) and lymph node yields (median 14 vs. 10 for VATS) [20].
- **Reduced morbidity:** Postoperative complications are lower, with pneumonia rates at 10% vs. 18% for VATS (OR = 0.52; 95% CI: 0.35–0.78; $p < 0.05$) and atrial fibrillation at 12% vs. 20%. Blood loss is minimized (100 mL vs. 150 mL), reducing transfusion needs [8].
- **Patient recovery:** Hospital stays are shorter (3–5 days vs. 5–7 days for VATS), and pain scores are reduced (VAS 2 vs. 4), lowering opioid use (50 mg vs. 80 mg morphine equivalent) and accelerating adjuvant therapy [21].
- **Ergonomics:** Surgeons report 30% less fatigue due to the console design, improving focus during long procedures (e.g., esophagectomy: 300–400 min) [22].
- **Oncologic efficacy:** Survival rates match VATS and open surgery (e.g., 5-year OS 80% in lung cancer), with trends toward lower recurrence (12% vs. 15%) [23].

These benefits position RATS as a valuable tool in thoracic surgery, particularly for complex oncologic cases requiring meticulous dissection and rapid recovery.

CHALLENGES AND LIMITATIONS

Despite its advantages, RATS faces serious obstacles to widespread clinical application. It is necessary to mention primarily such factors as:

- **Economic burden:** System acquisition costs range from €920,000 to €1,840,000, with per-case expenses of €2,760–€4,600, far exceeding VATS (€1,840–€2,760) and open surgery (€1,380–€1,840) [2]. High-volume centers may offset this through reduced complications, but smaller institutions struggle.
- **Operative time:** Procedures take longer – 180–240 min for lobectomy, 300–400 min for esophagectomy – versus 150–200 min and 250–300 min for VATS, increasing anesthesia risks and operating room costs [9].
- **Learning curve:** Proficiency requires 20–50 cases, with initial complication rates 10% higher during training, necessitating dedicated programs [24].
- **Limited evidence:** Only 3 RCTs exist as of 2025, with most data from observational studies, limiting definitive comparisons to VATS or open surgery [25].
- **Equity issues:** High costs restrict RATS to well-funded centers, exacerbating disparities in low-resource settings, where adoption lags [26].

These challenges highlight the need for cost reduction, streamlined training, and robust clinical trials to secure RATS' place in thoracic surgery.

TECHNOLOGICAL ADVANCEMENTS AND FUTURE DIRECTIONS

The future of RATS is shaped by cutting-edge and dynamically developing practical innovations such as:

- **AI integration:** Machine learning enhances preoperative planning and intraoperative navigation, potentially improving resection margins and nodal sampling [10].
- **Single-port systems:** Platforms reducing incisions to 1–2 cm improve cosmesis and recovery, nearing widespread use [11].
- **Haptic feedback:** Next-generation systems restore tactile sensation, addressing a VATS advantage, with clinical trials underway [17].
- **Training simulators:** Virtual reality cuts learning curves by 30%, broadening surgeon access [27].
- **Long-term outlook:** Cost reductions (e.g., patent expirations), autonomous suturing, and real-time imaging could democratize RATS, making it a standard of care [12].

These advancements promise to overcome current limitations, enhancing RATS' role in thoracic oncology.

DISCUSSION AND CONCLUSION

RATS has undeniably carved a significant niche in modern thoracic surgery, particularly in the realm of thoracic oncology, where its technical precision, reduced morbidity, and enhanced patient recovery profiles offer compelling advantages. Currently RATS stands as a transformative tool, complementing and, in certain contexts, surpassing the capabilities of VATS and traditional open thoracotomy. Its current applications – most notably in lung cancer resection, mediastinal tumor management, and esophageal cancer surgery – demonstrate its capacity to address the complex demands of oncologic care, where achieving complete resection (R0), robust lymph node harvest, and long-term survival are paramount. For lung cancer, RATS achieves a 5-year overall survival (OS) of 80%, matching VATS and open surgery, while improving lymph node yields (median 14 vs. 10 for VATS) and reducing complications like pneumonia (10% vs. 18%) and atrial fibrillation (12% vs. 20%) [5, 8]. In mediastinal tumor resection, particularly thymomas, it secures R0 resection rates of 96% with lower morbidity and shorter hospital stays (3 days vs. 7 days for sternotomy) [13]. For esophageal cancer, RATS reduces anastomotic leaks (5% vs. 20% for VATS), enhancing postoperative recovery and oncologic outcomes [24]. These metrics underscore RATS' ability to deliver oncologic efficacy comparable to or better than established methods while minimizing patient trauma.

Its economic footprint – system acquisition costs of €920,000–€1,840,000 and per-case expenses of €2,760–€4,600 – far exceeds that of VATS (€1,840–€2,760) and open surgery (€1,380–€1,840), posing a significant barrier to widespread adoption [2]. This cost differential is particularly pronounced in smaller institutions or low-resource settings, where financial constraints limit access to robotic platforms, exacerbating global disparities in surgical care [26]. Moreover, the steep learning curve (20–50 cases) required to achieve proficiency introduces additional challenges, with initial complication rates 10% higher during training phases, necessitating structured mentorship and simulation programs [24]. The paucity of long-term randomized controlled trials (RCTs) – only 3 as of 2025 – further complicates its validation, as most evidence derives from observational studies, leaving gaps in definitive comparisons to VATS or open surgery [25]. These limitations temper RATS dominance, positioning it as a complementary rather than a replacement technology in many centers, particularly where VATS remains efficient and cost-effective for straightforward cases.

Looking forward, the trajectory of RATS hinges on technological innovation and strategic policy shifts. Advances such as artificial intelligence (AI)-driven navigation, single-port systems, and haptic feedback hold transformative potential. AI could refine resection margins and lymph node sampling, potentially reducing recurrence rates (currently 12% vs. 15% for VATS) and enhancing survival [10]. Single-port systems, reducing incisions to 1–2 cm, promise improved cosmesis and faster recovery, with clinical adoption nearing reality [11]. Haptic feedback, addressing a key VATS advantage, is in late-stage trials and could improve nerve preservation and operative finesse by 2030 [17]. Virtual reality simulators, cutting learning curves by 30%, may democratize training, enabling broader surgeon proficiency [27]. These developments, coupled with anticipated cost reductions – such as patent expirations lowering system prices – could make RATS more accessible, potentially establishing it as a standard of care by 2030 [12]. However, realizing this vision requires concerted efforts beyond technology: health policy must prioritize funding models that balance initial investment with long-term savings from reduced complications and shorter hospital stays, while international collaboration could address equity gaps.

RATS current strengths – precision, reduced morbidity, and patient-centered outcomes – position it as an invaluable tool in high-volume, specialized centers, particularly for complex oncologic cases where VATS limitations (e.g., 2D imaging, rigid tools) are most apparent. Its ability to expedite adjuvant anticancer therapy through faster recovery (e.g., 3–5 days hospital stay vs. 5–7 days for VATS) is a critical advantage in cancer care, where timing is often decisive [21]. Yet, its scalability remains constrained by economic and evidentiary hurdles. To secure a lasting place, RATS must evolve from a luxury to a necessity, a transition that demands robust RCTs to quantify its benefits (e.g., cost-benefit analyses, survival gains) and innovative financing to bridge access divides. If these challenges are met, RATS could redefine thoracic surgery standards in the coming years, shifting the paradigm toward personalized, technology-driven care.

In conclusion, RATS has a definitive and expanding role in modern thoracic oncosurgery with its future contingent on overcoming economic, training, and evidence barriers through innovation and policy reform, potentially heralding a new era of surgical precision and equity.

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