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Global Evolution of Precision Surgery for Pulmonary Nodules: Linking Bibliometric Trends to Clinical Evidence Maturity, 1995-2026

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Research

Global Evolution of Precision Surgery for Pulmonary Nodules: Linking Bibliometric Trends to Clinical Evidence Maturity, 1995-2026

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Abstract

Background: Precision surgery for pulmonary nodules increasingly integrates localization, navigation, three-dimensional planning, image guidance, and minimally invasive or robotic resection. Yet rapid publication growth and technological diversification do not necessarily indicate parallel maturation of clinical evidence. We mapped the technological evolution of the field and assessed how far major technology domains have progressed through clinical evaluation.

Methods: We defined six non-mutually exclusive technology domains and assessed eligible primary studies using an ordered evidence-maturity framework ranging from EM0 (preclinical/technical development) to EM5 (randomized evaluation). Bibliometric and network analyses of the Web of Science Core Collection characterized temporal, geographic, collaborative, thematic, and citation structures, while targeted clinical contextualization linked these patterns to operative practice. English-language articles and reviews published from 1995 through 2026 were retrieved on August 27, 2026; 2026 was treated as a partial observation year. The final corpus comprised 1,308 publications, including 1,133 primary studies eligible for ordered maturity assessment.

Results: Of 1,308 publications, 754 (57.6%) appeared during 2020-2026. Among 1,133 eligible primary studies, the proportion at EM3-EM5 increased from 14.0% in 1995-2009 to 40.0% in 2020-2026, yet only 39 studies (3.4%) reached EM4-EM5. Evidence maturity varied across technology domains: precision resection had the highest EM3-

EM5 proportion (92/203, 45.3%), whereas later-stage evaluation remained less common in localization, navigation, minimally invasive innovation, robotic thoracic surgery, and advanced guided/integrated surgery. The field evolved from standalone percutaneous and bronchoscopic localization toward anatomy-based sublobar resection and increasingly integrated workflows incorporating cone-beam computed tomography, three-dimensional reconstruction, fluorescence, augmented reality, and robotic platforms.

Conclusions: Technological expansion and integration have outpaced prospective controlled and randomized evaluation. The principal translational challenge has therefore shifted from demonstrating technical feasibility to establishing reproducible incremental clinical value. Stage-matched multicenter prospective studies with standardized, clinically meaningful endpoints are needed across technology domains.

Keywords: pulmonary nodules; precision surgery; clinical evidence maturity; bibliometric analysis; surgical innovation

Background

Low-dose computed tomography (LDCT) screening has reshaped the clinical setting in which pulmonary nodules are detected and managed. In the National Lung Screening Trial, LDCT reduced lung cancer mortality by 20.0% relative to chest radiography among high-risk participants [1]. The NELSON randomized trial subsequently confirmed a mortality benefit with volume-based CT screening, reporting a 10-year lung cancer mortality rate ratio of 0.76 in the primary male cohort [2]. By increasing the detection of small pulmonary lesions at an early and potentially curable stage, these trials also increased the clinical importance of precise nodule management [1, 2].

The operative strategy for small peripheral lung cancer has changed in parallel. Lobectomy became the standard resection for operable early-stage non-small cell lung cancer (NSCLC) after the Lung Cancer Study Group randomized trial showed substantially greater local recurrence after limited resection [3]. More recent phase III trials refined this paradigm in carefully selected tumors. JCOG0802/WJOG4607L demonstrated superior overall survival after segmentectomy in patients with peripheral clinical stage IA NSCLC measuring ≤2 cm, although local relapse was more frequent than after lobectomy [4], whereas CALGB/Alliance 140503

showed noninferior disease-free survival after sublobar resection in patients with peripheral, node-negative NSCLC measuring ≤2 cm [5]. Together, these trials shifted the question from whether less lung can be removed to how the extent of resection can be individualized while preserving adequate margins, nodal assessment, and oncologic control [4, 5].

Concurrently, the technologies used to target and resect pulmonary nodules have diversified. CT-guided localization and bronchoscopic mapping facilitated resection of small or impalpable lesions [6, 7], while electromagnetic navigation, patient-specific three-dimensional planning, and robot-assisted approaches increasingly connected lesion targeting, anatomical planning, and minimally invasive resection [8-10]. Rather than being defined by a single device or resection platform, contemporary precision surgery increasingly operates as an integrated pathway linking localization, navigation-assisted targeting, patient-specific bronchovascular planning, margin-oriented resection, nodal assessment, intraoperative image or fluorescence guidance, and minimally invasive or robotic execution (Figure 1). These components emerged along different timelines but increasingly converge within the same operative episode.

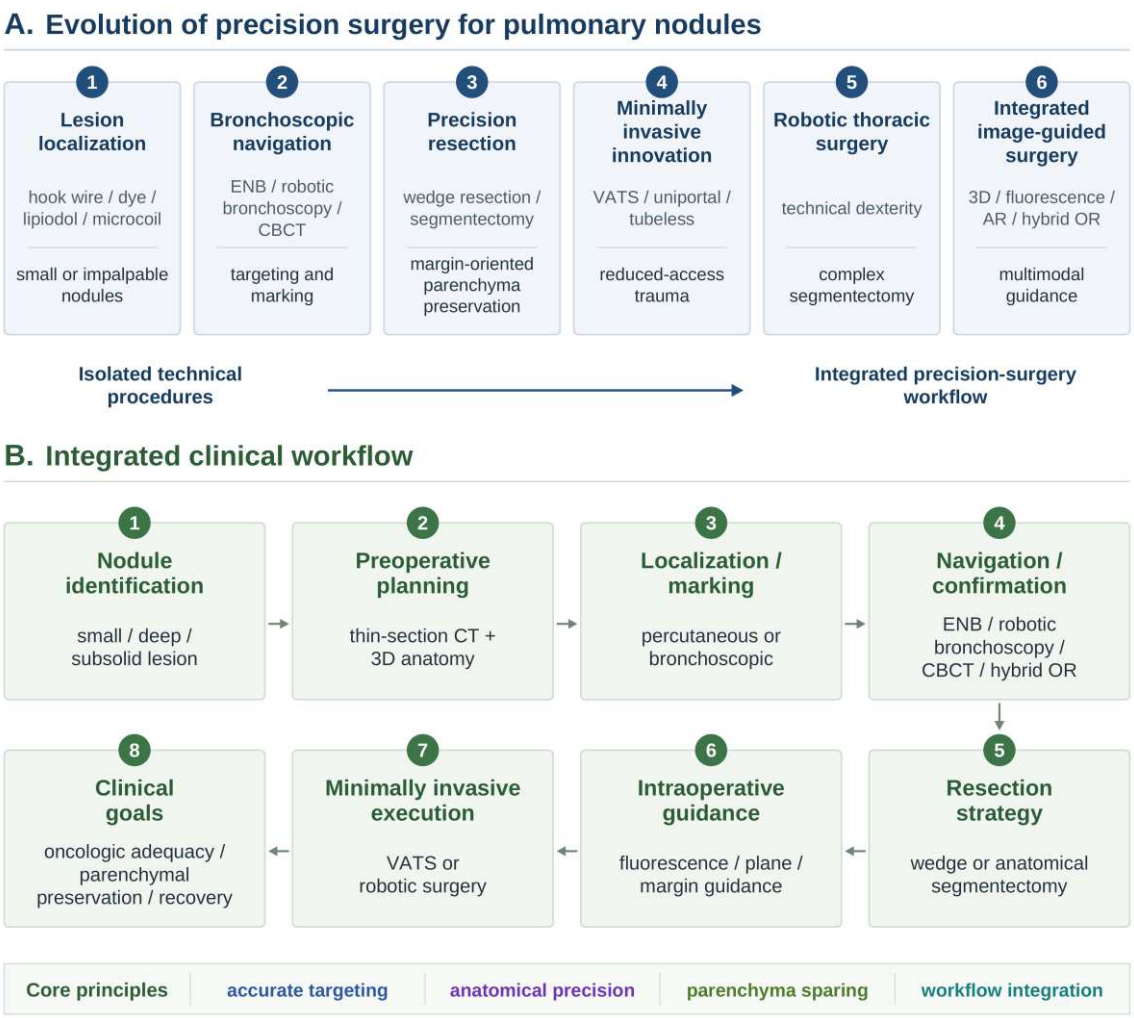


Figure 1. Evolution and integrated workflow of precision surgery for pulmonary nodules. (A) Progression from localization to navigation, precision resection, minimally invasive/robotic surgery, and integrated image guidance. (B) Workflow from planning and localization/confirmation through resection and guidance to clinical goals. AR, augmented reality; CBCT, cone-beam CT; ENB, electromagnetic navigation bronchoscopy; VATS, video-assisted thoracic surgery.

Rationale and knowledge gap

Yet technological expansion and research visibility do not establish clinical maturity. The IDEAL framework emphasizes staged evaluation of surgical innovation from development and exploration through comparative assessment and, where feasible, randomized evaluation [11]. Existing bibliometric studies have mapped publication growth, collaboration, keywords, citations, and research fronts in pulmonary nodule research and sublobar surgery [12, 13]. These approaches identify where scientific attention and connectivity are accumulating, but they do not determine whether the underlying technologies have progressed from technical feasibility to comparative, prospective controlled, or randomized clinical evaluation. A field-level assessment that links technological evolution to the stage of clinical evaluation is therefore needed.

Objective

To address this gap, we sought to determine whether the rapid technological expansion of precision surgery for pulmonary nodules has been accompanied by comparable maturation of clinical evidence. We mapped six non-mutually exclusive technology domains and assessed eligible primary studies using the ordered EM0-EM5 framework. Bibliometric and network analyses characterized the temporal, geographic, collaborative, thematic, and citation structures within which these translational trajectories evolved, while targeted clinical contextualization related the quantitative findings to operative practice.

Methods

Retrieval strategy

The Web of Science Core Collection (WoSCC) was searched on August 27, 2026, for English-language publications classified as Article or Review Article and published from 1995 through 2026 on precision surgery for pulmonary nodules. The strategy combined three conceptual domains: pulmonary nodules, precision localization or resection technologies, and surgical procedures. Because the search preceded completion of the 2026 calendar year, 2026 was treated as a partial observation year in temporal analyses. The complete topical search strategy was:

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TS=(
  "pulmonary nodule*" OR "lung nodule*" OR "solitary pulmonary nodule*" OR "subsolid nodule*" OR "sub-solid nodule*" OR "ground glass opacity*" OR "ground-glass opacity*" OR "ground glass nodule*" OR "ground-glass nodule*" OR ((GGO OR GGN) NEAR/3 (lung OR pulmonary OR nodule*))
)
AND TS=(
  localization* OR localisation* OR "preoperative localization" OR "preoperative marking" OR "nodule localization" OR "pulmonary nodule localization" OR "CT-guided localization" OR "virtual-assisted lung mapping" OR "VAL-MAP" OR microcoil OR "micro coil" OR "hook wire" OR "hook-wire" OR hookwire OR "fiducial marker*" OR "indocyanine green" OR "methylene blue" OR "bronchoscopic navigation" OR "electromagnetic navigation bronchoscopy" OR "robotic bronchoscopy" OR "virtual bronchoscopy" OR "cone-beam CT" OR "cone
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beam CT" OR segmentectom* OR subsegmentectom* OR "sublobar resection" OR "sub-lobar resection" OR "wedge resection" OR "limited resection" OR "3D reconstruction" OR "three-dimensional reconstruction" OR "image-guided surgery" OR "augmented reality"
)
AND TS=(
surgery OR surgical OR resection OR operation* OR operative OR VATS OR "video-assisted thoracic surgery" OR "thoracoscopic surgery" OR thoracoscop* OR "minimally invasive surgery" OR "robot-assisted thoracic surgery" OR "robotic-assisted thoracic surgery" OR "robotic thoracic surgery"
)

Publication selection and data extraction

After bibliographic integrity cleaning, 1,914 records underwent eligibility screening. Two investigators independently screened titles and abstracts against predefined criteria encompassing the pulmonary-nodule, surgical, and precision-technology scope. Records with discordant judgments or uncertain eligibility were independently reviewed by a third investigator, with additional record-level information consulted when needed to determine eligibility. The final corpus comprised 1,308 publications and served as the source dataset for all subsequent analyses. The study-selection flow is shown in Supplementary Figure S5, and detailed eligibility and screening criteria are provided in Supplementary Table S1 [see Additional file 1].

Bibliographic data extracted from the Web of Science records included publication year, document type, authors, affiliations, enhanced organizations, countries or regions, Author Keywords, cited references, and citation counts. Global citation counts were based on Web of Science Times Cited values at the database cutoff. DOI-normalized links were additionally used to identify citation relationships recoverable within the 1,308-publication corpus; because references without resolvable DOIs could not be linked, these values were treated as DOI-resolved within-corpus citation links rather than a complete local citation score.

Technology classification and evidence-maturity assessment

Technology classification was designed to capture the operative function of precision-surgery strategies across the literature. Two investigators independently evaluated every included publication against six predefined, non-mutually exclusive domains (Table 1): localization (T1), navigation (T2), precision resection (T3), minimally invasive surgery innovation (T4), robotic thoracic surgery (T5), and advanced guided/integrated surgery (T6). One or more labels were assigned only when the corresponding technology or strategy constituted a substantive component of the study; publications meeting none of the domain-specific criteria remained unlabeled for this analysis. Classification was based primarily on titles, abstracts, and Author Keywords, with Keywords Plus used only as supportive context. Disagreements or uncertain technology assignments were adjudicated by a third investigator. Detailed operational criteria are provided in Supplementary Table S2.

Table 1. Operational definitions of technology domains and evidence-maturity stages

Framework	Code/category	Operational definition
Technology domain	T1 Localization	Substantive preoperative or intraoperative localization or marking used to enable operative identification or resection of a pulmonary nodule.
Technology domain	T2 Navigation	Navigation used substantively for surgical localization, marking, targeting, planning, or resection; diagnostic- or biopsy-only navigation was excluded.
Technology domain	T3 Precision resection	Resection extent or strategy, segment/subsegment selection, intersegmental-plane definition, margin strategy, limited/sublobar strategy, or parenchymal preservation as a substantive study focus.
Technology domain	T4 MIS innovation	Uniportal, single-port, subxiphoid, non-intubated, tubeless, needlescopic, or related minimally invasive access/workflow innovation as a substantive study focus.
Technology domain	T5 Robotic thoracic surgery	Robot-assisted thoracic surgical technique or platform as a substantive focus; robotic bronchoscopy and robot-assisted percutaneous localization were excluded.
Technology domain	T6 Advanced guided/integrated surgery	Advanced technology substantively integrated into the surgical workflow, including fluorescence/NIR imaging, cone-beam/intraoperative CT or hybrid-OR guidance, three-dimensional or augmented/virtual-reality planning, advanced optical/robotic navigation, radioguided techniques, sensor-guided localization, or integrated hybrid workflows.
Evidence maturity	EM0 Preclinical/technical development	Preclinical, nonhuman, phantom, ex vivo, cadaveric, or other technical-development evidence without clinical validation.
Evidence maturity	EM1 Initial clinical feasibility	Early human clinical use primarily establishing feasibility, technical execution, or initial safety.
Evidence maturity	EM2 Clinical validation	Clinical validation in humans without a comparative clinical design meeting EM3 or higher.
Evidence maturity	EM3 Comparative clinical validation	Comparative clinical evaluation between relevant procedures, techniques, technologies, or comparator groups.
Evidence maturity	EM4 Prospective controlled evaluation	Prospective controlled comparative clinical evaluation without random allocation.
Evidence maturity	EM5 Randomized evaluation	Randomized clinical evaluation.

Clinical evidence maturity was assessed independently of technology classification to determine how far each eligible primary study reporting original results had progressed along the clinical

evaluation pathway. Two investigators independently assigned eligible studies to six ordered stages: EM0, preclinical or technical development; EM1, initial clinical feasibility; EM2, clinical validation; EM3, comparative clinical validation; EM4, prospective controlled evaluation; and EM5, randomized evaluation. Assignment incorporated study role, study design, temporal design, and comparator structure. Protocol-only publications were excluded from ordered maturity analyses, whereas evidence syntheses and guidance documents remained in the bibliometric corpus but were not positioned on the EM0-EM5 sequence. The ordered analyses therefore comprised 1,133 eligible primary studies. Disagreements or uncertain maturity assignments were adjudicated by a third investigator. The EM framework represents the stage of clinical evaluation rather than methodological quality, risk of bias, certainty of evidence, or treatment-effect magnitude. Detailed operational criteria are provided in Supplementary Table S3.

Clinical contextualization

To interpret the quantitative bibliometric and evidence-maturity findings in the context of operative practice, we conducted a milestone-oriented clinical contextualization of the principal precision-surgery pathways for pulmonary nodules: lesion localization, bronchoscopic navigation and image-guided targeting, precision resection, minimally invasive surgical innovation, robotic thoracic surgery, three-dimensional planning, fluorescence guidance, and integrated image-guided surgery. Representative publications were selected for their relevance to major technical milestones, clinical implementation, comparative development, and emerging technologies. Contextualization drew primarily from the bibliometric corpus; landmark or contextual publications outside the predefined eligibility criteria or publication period were consulted when needed to establish historical or clinical context. These external references informed interpretation only and did not enter publication counts, network analyses, technology-domain distributions, or evidence-maturity calculations. This component was narrative and milestone-oriented rather than a formal systematic review or meta-analysis.

Data analysis

All analyses used the fixed 1,308-publication corpus, with analysis-specific study sets and thresholds specified below. Publication years were grouped into four descriptive eras: 1995-2009, 2010-2014, 2015-2019, and 2020-2026. Country-level publication, technology, and evidence profiles were derived from harmonized Web of Science address data using fractional counting, with each publication contributing 1/n to each of its n assigned countries; country information was assignable for 1,299 publications. Organization-level analyses used Web of Science enhanced-organization strings with exact-string deduplication within publications. Country profiles and the VOSviewer country co-authorship network were analyzed as complementary but distinct outputs: the former used the harmonized address-based dataset, whereas the latter used VOSviewer's own bibliographic parsing and fractional network calculation.

Network analyses were performed in VOSviewer version 1.6.21 [14] using association-strength normalization, clustering resolution 1.00, minimum cluster size 1, and the default layout. Country, institution, and author co-authorship networks used fractional counting with minimum publication thresholds of 5, 10, and 5, respectively; an eight-publication institution threshold was examined as a sensitivity analysis. Author Keyword co-occurrence used full counting after thesaurus normalization, excluded Keywords Plus, and retained terms occurring at least five times in the principal network. Reference co-citation used full counting with a minimum of 30 citations after correction of one verified split reference, whereas document bibliographic coupling used fractional counting with a minimum of 25 global citations. Prespecified sensitivity analyses varied network inclusion thresholds, and interpretation emphasized stable macro-level structures rather than threshold-sensitive peripheral partitions. Country and author co-authorship maps are provided in Supplementary Figures S1 and S2, and threshold-sensitivity results are summarized in Supplementary Table S8.

Temporal research fronts were evaluated with CiteSpace 6.4.R1 Advanced [15] over 1995-2026 using one-year slices and the g-index (k = 25). Keyword bursts were derived from normalized Author Keywords, whereas cited-reference bursts used canonicalized cited references. Burst detection used two states, gamma = 1.0, a minimum duration of two years, and no pruning for burst-list generation. Because 2026 was an incomplete observation year, bursts extending to 2026 were treated as active at the database cutoff. Reference-level intellectual structure was evaluated separately by VOSviewer co-citation analysis; CiteSpace was used to characterize temporal burst dynamics.

For integrated interpretation, Author Keyword thematic groups were designated K1-K9 and bibliographic-coupling research communities R1-R6. These labels represent distinct analytical constructs and were not assumed to correspond one-to-one. Technology-domain profiles allowed multi-membership, evidence-maturity proportions were calculated within explicitly defined eligible study sets, and bibliographic-coupling profiles described the citation-thresholded mapped subset rather than whole-corpus prevalence. These analysis-specific definitions were retained throughout interpretation. Reporting was assessed against the BIBLIO guideline for bibliometric reviews of the biomedical literature [16]; the completed checklist is provided as Additional file 2 [see Additional file 2].

Results

Search process and temporal evolution of research activity and clinical evidence

Within the fixed corpus, 1,308 publications spanning 1995-2026 remained after eligibility screening of 1,914 records that had passed bibliographic integrity cleaning. Research output accelerated sharply after the mid-2010s: 145 publications (11.1%) appeared in 1995-2009, 104 (8.0%) in 2010-2014, 305 (23.3%) in 2015-2019, and 754 (57.6%) in 2020-2026. Among complete calendar years, output peaked in 2024 at 126 publications. The 97 publications recorded in 2026 represented an incomplete observation year at the database cutoff and were not treated as a completed annual total (Figure 2A).

Alongside this growth in output, the evidence profile shifted toward later-stage clinical evaluation. Among 1,133 primary studies eligible for ordered maturity analysis, EM2 clinical validation remained the dominant stage (584/1,133, 51.5%), followed by EM3 comparative clinical validation (316/1,133, 27.9%). The combined proportion at EM3-EM5 rose from 14.0% in 1995-2009 to 18.7% in 2010-2014, 23.6% in 2015-2019, and 40.0% in 2020-2026. Nevertheless, prospective controlled evaluation (EM4; 5/1,133, 0.4%) and randomized evaluation (EM5; 34/1,133, 3.0%) remained uncommon (Figure 2B).

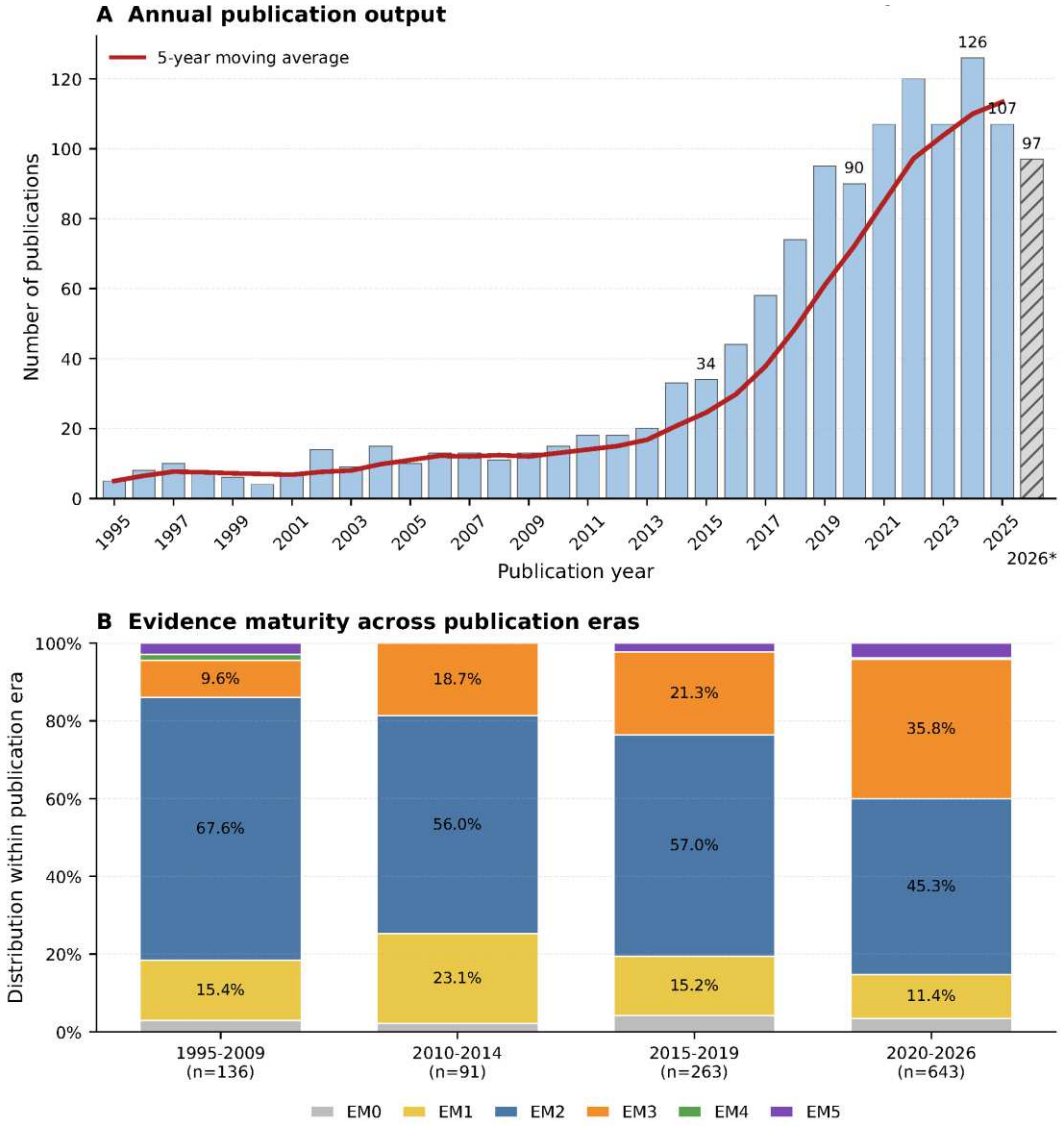


Figure 2. Temporal evolution of research activity and clinical evidence maturity. (A) Annual publication output from 1995 to 2026; the five-year moving average ends in 2025 and the hatched 2026 bar denotes an incomplete year. (B) EM0-EM5 distribution across four publication eras among maturity-eligible primary studies; EM0-EM5 span technical development through randomized evaluation.

Clinical evidence maturity across technology domains

This temporal maturation varied substantially across technology domains. Among primary studies eligible for maturity assessment, localization included 633 studies, advanced guided/integrated surgery 326, precision resection 203, navigation 73, MIS innovation 32, and robotic thoracic surgery 15; domain membership was non-mutually exclusive. Precision resection had the most advanced profile, with 92 of 203 studies (45.3%) reaching EM3-EM5. The corresponding proportions were 33.3% for robotic thoracic surgery, 32.9% for navigation, 29.9% for localization, 28.1% for MIS innovation, and 26.1% for advanced guided/integrated surgery. Across all domains, EM5 randomized evaluation remained rare, ranging from 0% to 4.3%. Table 2 summarizes the clinical roles and later-stage evaluation profiles, and Figure 3 shows the full EM0-EM5 distributions.

Table 2. Clinical roles and evidence profiles of the six precision-surgery technology domains

Technology domain	Clinical role and representative approaches	Eligible primary studies, n	EM3-EM5, n (%)	EM5, n (%)
T1 Localization	Lesion identification and operative targeting: hook-wire, microcoil, dye/ICG, VAL-MAP, RFID	633	189 (29.9)	25 (3.9)
T2 Navigation	Bronchoscopic and image-confirmed targeting: ENB, robotic bronchoscopy, CBCT-supported navigation	73	24 (32.9)	3 (4.1)
T3 Precision resection	Parenchyma-sparing resection strategy: wedge resection, segmentectomy/subsegmentectomy, margin- and plane-oriented planning	203	92 (45.3)	3 (1.5)
T4 MIS innovation	Access and perioperative workflow: uniportal, subxiphoid, non-intubated, tubeless approaches	32	9 (28.1)	1 (3.1)
T5 Robotic thoracic surgery	Robotic surgical execution: robot-assisted segmentectomy and related thoracic resection	15	5 (33.3)	0 (0.0)
T6 Advanced guided/integrated surgery	Multimodal planning and intraoperative guidance: fluorescence/NIR, 3D/AR/VR, CBCT/hybrid OR, radioguided or sensor-guided workflows	326	85 (26.1)	14 (4.3)

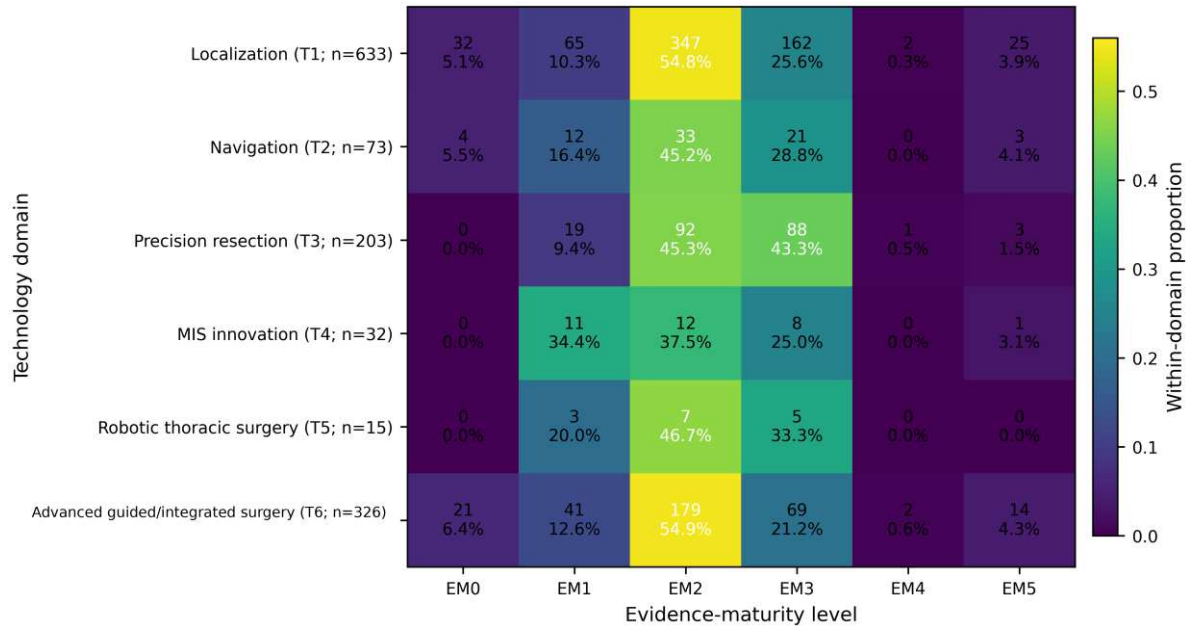


Figure 3. Clinical evidence maturity across technology domains. Cells show the number and within-domain percentage of eligible primary studies at EM0-EM5 for localization (T1), navigation (T2), precision resection (T3), MIS innovation (T4), robotic thoracic surgery (T5), and advanced guided/integrated surgery (T6). Domains are non-mutually exclusive.

Global contribution and country-level clinical profiles

Beyond these domain-level differences, research activity and evidence maturity also varied geographically. Country information was assignable for 1,299 of 1,308 publications. By harmonized address-based fractional counting, China contributed the largest output (528.3), followed by Japan (236.0), the United States (150.5), Italy (80.2), Taiwan (76.0), and South Korea (67.9) (Figure 4A). Among these six countries, the fractional proportion of primary studies eligible for maturity assessment that were classified as EM3-EM5 ranged from 16.3% in the United States to 43.7% in China, with Taiwan at 35.6%, Japan at 24.6%, Italy at 21.4%, and South Korea at 20.2%. Country-level maturity percentages are descriptive because the number of eligible primary studies differed by country; complete results are provided in Supplementary Table S4.

National research portfolios also differed in technology composition (Figure 4B). Localization was particularly prominent in Taiwan (77.2% of fractional output) and Italy (65.8%), whereas precision resection accounted for a larger share in Japan (35.2%) and South Korea (24.3%). Advanced guided/integrated surgery was most prominent among the 10 highest-output countries in Italy (55.3%), Taiwan (45.6%), and France (40.1%), followed by Canada (33.0%) and the

United States (30.5%). Because technology domains were non-mutually exclusive, within-country percentages could exceed 100% in aggregate. Country-level evidence-maturity distributions are shown in Figure 4C.

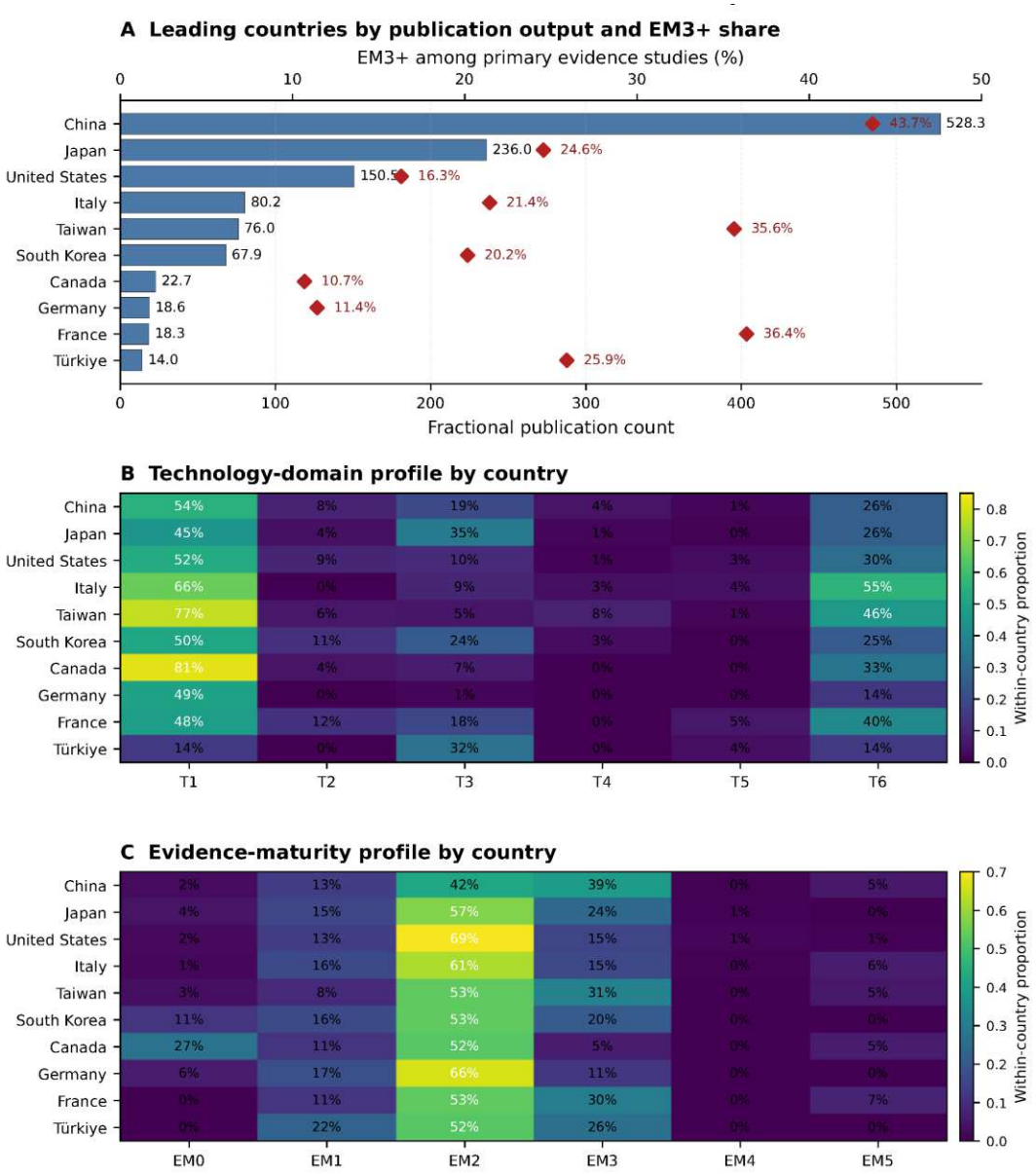


Figure 4. Global contribution and country-level clinical evidence profiles. (A) Leading countries by fractional publication output; diamonds show the proportion of primary studies at EM3 or higher. (B) Technology-domain composition. (C) Evidence-maturity distribution among eligible primary studies. Domains are non-mutually exclusive. Fractional country attribution was available for 1,299 of 1,308 publications.

Thematic architecture and temporal evolution

Thematic mapping provided a complementary view of how research emphases changed over time. The author-keyword network resolved 117 keywords into nine thematic groups (K1-K9), revealing a field anchored by localization and sublobar resection but increasingly extended by image-guided and navigational technologies (Figure 5A). The largest groups were K4, centered

on preoperative CT-guided localization for VATS (861 cumulative occurrences), and K2, centered on ground-glass/early lung cancer and sublobar resection (799 occurrences). The remaining groups captured CT-oriented thoracic surgery and diagnostic context (K1), pulmonary nodule localization and marking methods (K3), fluorescence and intraoperative image guidance (K5), navigation bronchoscopy and hybrid-OR localization (K6), emerging robotic-assisted localization and margin-oriented techniques (K7), radioguided/lipiodol localization (K8), and thoracoscopy with 3D-guided segmentectomy (K9).

Temporal overlay analysis separated established themes from newer research fronts. K7 had the latest occurrence-weighted mean publication year (2023.3), followed by K5 (2021.1) and K6 (2020.7), whereas K1 was earlier (2018.4) (Figure 5B). A higher keyword-occurrence threshold produced moderate changes in finer cluster boundaries but preserved the principal thematic architecture, supporting interpretation at the macro-theme level (Supplementary Figure S4B). The complete 117-keyword dataset and K1-K9 summaries are provided in Supplementary Table S5.

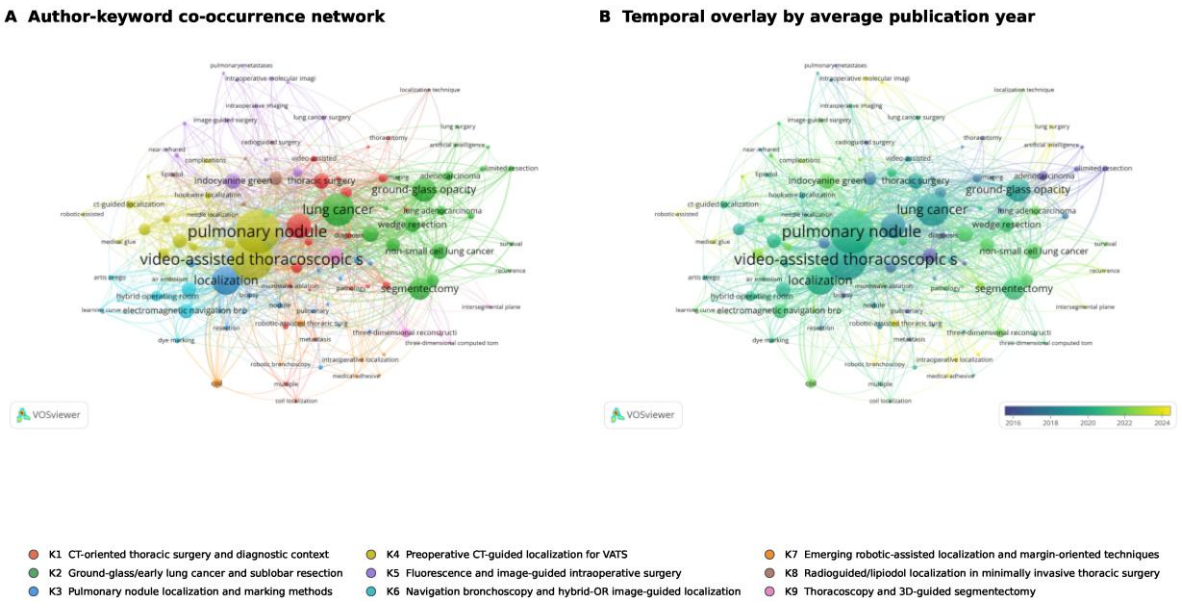


Figure 5. Author keyword thematic architecture and temporal evolution. (A) VOSviewer co-occurrence network, with node size representing occurrences, links co-occurrence, and colors thematic groups K1-K9. (B) Temporal overlay of the same network, with node color indicating average publication year.

Clinical trajectories across bibliographic-coupling research communities

These thematic patterns were also reflected in the bibliographic-coupling structure, which identified six major communities spanning lesion localization, sublobar resection, and newer image-guided approaches (Figure 6). Of 321 citation-rich publications entering the coupling map, 309 formed six major communities (R1-R6). The earliest and largest community, R1 (n = 99; mean publication year 2006.8), centered on CT-guided and percutaneous localization before thoracoscopic resection. R2 (n = 91) linked ground-glass and early lung cancer with sublobar resection and was the most highly cited major community (mean global citation count 88.5). The more recent communities, concentrated around 2018, represented contemporary image-guided localization (R3, n = 72), precision segmental surgery supported by 3D planning or lung mapping (R4, n = 22), fluorescence or molecular guidance (R5, n = 16), and non-intubated, tubeless, and uniportal approaches (R6, n = 9). The underlying coupling network is shown in Supplementary Figure S3.

These citation-defined communities also differed in clinical maturity and technological composition. R4 had the highest concentration of later-stage evaluation, with 6 of 15 primary studies eligible for maturity assessment (40.0%) reaching EM3-EM5. R5 was dominated by advanced guided/integrated surgery, whereas R6 was characterized mainly by MIS innovation (Figure 6). Cross-network correspondence was substantial but incomplete: 209 of 321 mapped publications (65.1%) shared at least one selected K-group membership, with the strongest alignments between R2 and K2, R3 and K4/K6, and R5 and K5. Detailed R1-R6 profiles and K1-K9 overlap are provided in Supplementary Table S6, with the higher-threshold sensitivity network in Supplementary Figure S4D. Because the coupling map required at least 25 global citations, R1-R6 represent influential citation-rich trajectories rather than whole-corpus prevalence.

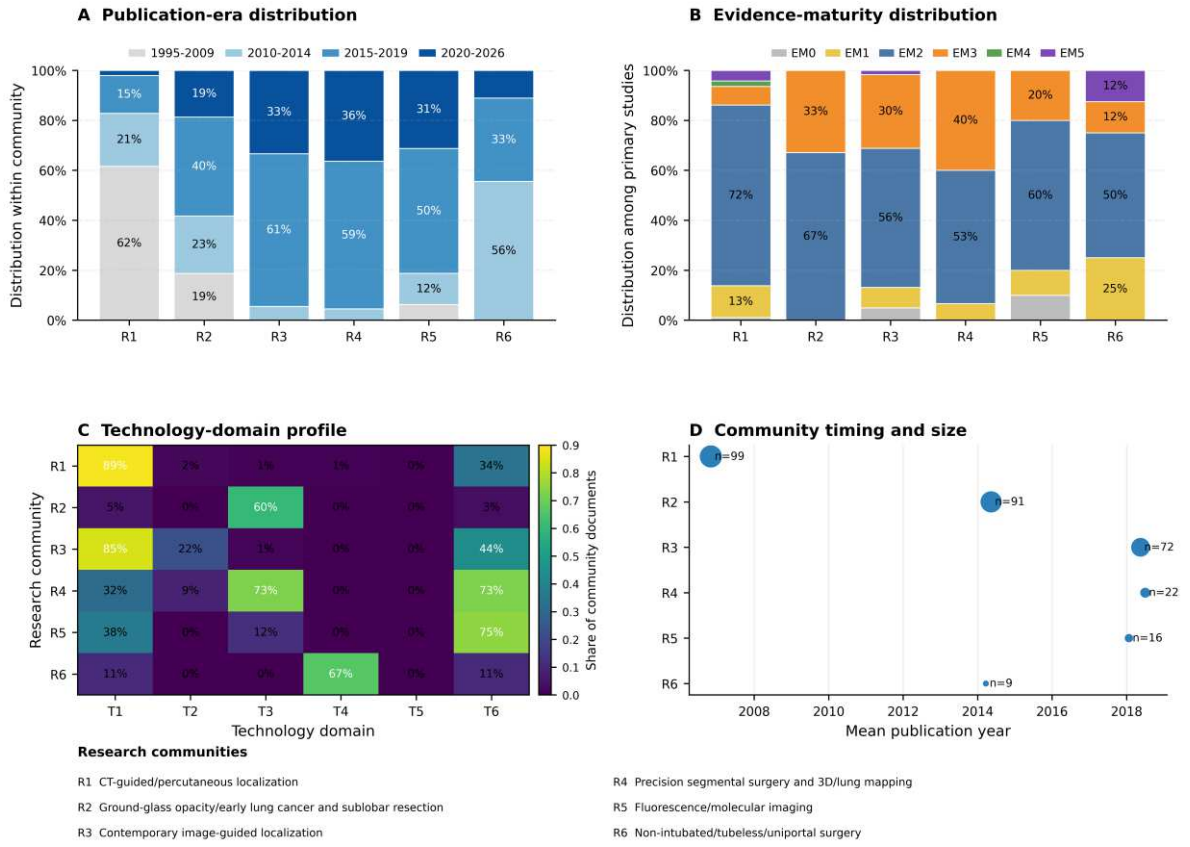


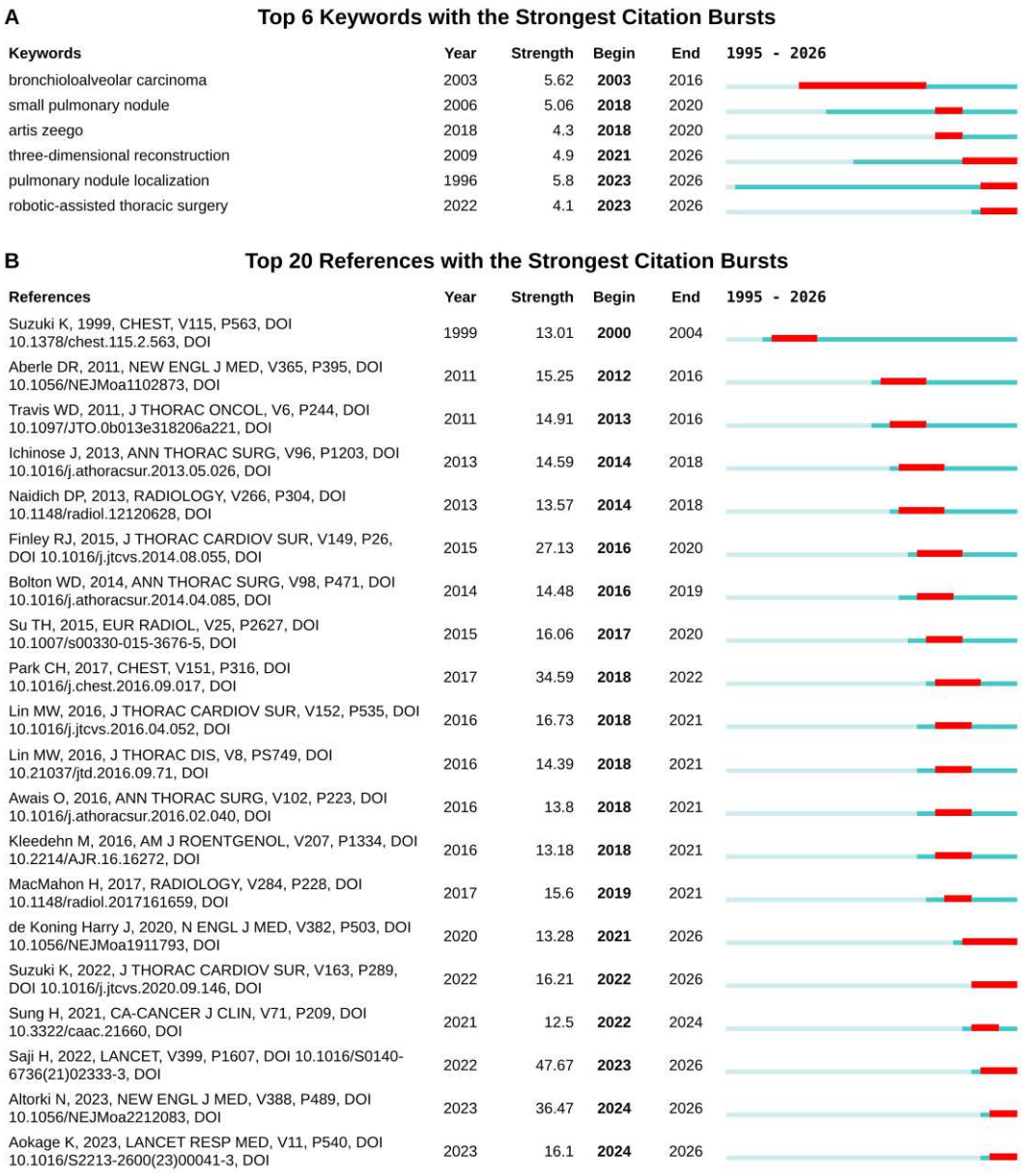
Figure 6. Clinical and temporal trajectories across bibliographic-coupling communities R1-R6. Profiles show publication era, evidence maturity, technology composition, and mean publication year. The map included 321 publications with at least 25 global citations; R1-R6 contained 309. Evidence maturity uses eligible primary studies, domains are non-mutually exclusive, and citation-thresholded profiles are not whole-corpus prevalence.

Temporal research fronts

Temporal burst analysis further identified research fronts that gained attention at different points in the observation period (Figure 7A). Bronchioloalveolar carcinoma showed the earliest sustained burst (strength 5.62; 2003-2016), whereas small pulmonary nodule and Artis Zeego burst during 2018-2020. Three-dimensional reconstruction emerged from 2021 and remained active at the 2026 observation cutoff. The strongest recent burst was pulmonary nodule localization (strength 5.80; 2023-2026), accompanied by robotic-assisted thoracic surgery (strength 4.10; 2023-2026). Bursts extending to 2026 were treated as active at the database cutoff because the 2026 observation year was incomplete.

At the cited-reference level, 237 references exhibited citation bursts, with the strongest recent signals centered on landmark trials and influential localization studies. Saji et al. (2022) showed the strongest burst (strength 47.67; 2023-2026), followed by Altorki et al. (2023; strength 36.47; 2024-2026), Park et al. (2017; strength 34.59; 2018-2022), and Finley et al. (2015; strength

27.13; 2016-2020). Forty-seven of the 237 bursts remained active at the 2026 observation cutoff. Figure 7B displays the 20 strongest cited-reference bursts by burst onset, and complete results are provided in Supplementary Table S7 [see Additional file 3].



A **Top 6 Keywords with the Strongest Citation Bursts**

Keywords	Year	Strength	Begin	End	1995 - 2026
bronchioloalveolar carcinoma	2003	5.62	2003	2016	
small pulmonary nodule	2006	5.06	2018	2020	
artis zeego	2018	4.3	2018	2020	
three-dimensional reconstruction	2009	4.9	2021	2026	
pulmonary nodule localization	1996	5.8	2023	2026	
robotic-assisted thoracic surgery	2022	4.1	2023	2026	

B **Top 20 References with the Strongest Citation Bursts**

References	Year	Strength	Begin	End	1995 - 2026
Suzuki K, 1999, CHEST, V115, P563, DOI 10.1378/chest.115.2.563, DOI	1999	13.01	2000	2004	
Aberle DR, 2011, NEW ENGL J MED, V365, P395, DOI 10.1056/NEJMoa1102873, DOI	2011	15.25	2012	2016	
Travis WD, 2011, J THORAC ONCOL, V6, P244, DOI 10.1097/JTO.0b013e318206a221, DOI	2011	14.91	2013	2016	
Ichinose J, 2013, ANN THORAC SURG, V96, P1203, DOI 10.1016/j.athoracsur.2013.05.026, DOI	2013	14.59	2014	2018	
Naidich DP, 2013, RADIOLOGY, V266, P304, DOI 10.1148/radiol.12120628, DOI	2013	13.57	2014	2018	
Finley RJ, 2015, J THORAC CARDIOV SUR, V149, P26, DOI 10.1016/j.jtcvs.2014.08.055, DOI	2015	27.13	2016	2020	
Bolton WD, 2014, ANN THORAC SURG, V98, P471, DOI 10.1016/j.athoracsur.2014.04.085, DOI	2014	14.48	2016	2019	
Su TH, 2015, EUR RADIOL, V25, P2627, DOI 10.1007/s00330-015-3676-5, DOI	2015	16.06	2017	2020	
Park CH, 2017, CHEST, V151, P316, DOI 10.1016/j.chest.2016.09.017, DOI	2017	34.59	2018	2022	
Lin MW, 2016, J THORAC CARDIOV SUR, V152, P535, DOI 10.1016/j.jtcvs.2016.04.052, DOI	2016	16.73	2018	2021	
Lin MW, 2016, J THORAC DIS, V8, PS749, DOI 10.21037/jtd.2016.09.71, DOI	2016	14.39	2018	2021	
Awais O, 2016, ANN THORAC SURG, V102, P223, DOI 10.1016/j.athoracsur.2016.02.040, DOI	2016	13.8	2018	2021	
Kleedehn M, 2016, AM J ROENTGENOL, V207, P1334, DOI 10.2214/AJR.16.16272, DOI	2016	13.18	2018	2021	
MacMahon H, 2017, RADIOLOGY, V284, P228, DOI 10.1148/radiol.2017161659, DOI	2017	15.6	2019	2021	
de Koning Harry J, 2020, N ENGL J MED, V382, P503, DOI 10.1056/NEJMoa1911793, DOI	2020	13.28	2021	2026	
Suzuki K, 2022, J THORAC CARDIOV SUR, V163, P289, DOI 10.1016/j.jtcvs.2020.09.146, DOI	2022	16.21	2022	2026	
Sung H, 2021, CA-CANCER J CLIN, V71, P209, DOI 10.3322/caac.21660, DOI	2021	12.5	2022	2024	
Saji H, 2022, LANCET, V399, P1607, DOI 10.1016/S0140-6736(21)02333-3, DOI	2022	47.67	2023	2026	
Altorki N, 2023, NEW ENGL J MED, V388, P489, DOI 10.1056/NEJMoa2212083, DOI	2023	36.47	2024	2026	
Aokage K, 2023, LANCET RESP MED, V11, P540, DOI 10.1016/S2213-2600(23)00041-3, DOI	2023	16.1	2024	2026	

Figure 7. Temporal research fronts identified by burst analysis. (A) Burst history for all six detected Author Keywords. (B) Burst history for the 20 cited references with the strongest bursts, selected by burst strength. Red segments denote burst intervals within 1995-2026; bursts ending in 2026 were active at the incomplete-year database cutoff.

Institutional collaboration structure

Collaboration analysis then showed how this research activity was organized institutionally. At the principal threshold of at least 10 publications per organization, 47 organizations formed a single connected network (Figure 8). Shanghai Jiao Tong University had the largest publication

count (53), followed by Fudan University (39), Nanjing Medical University (35), National Taiwan University Hospital (32), and Tongji University (30). Prominent collaboration cores were concentrated in China, Japan, Taiwan, and North America.

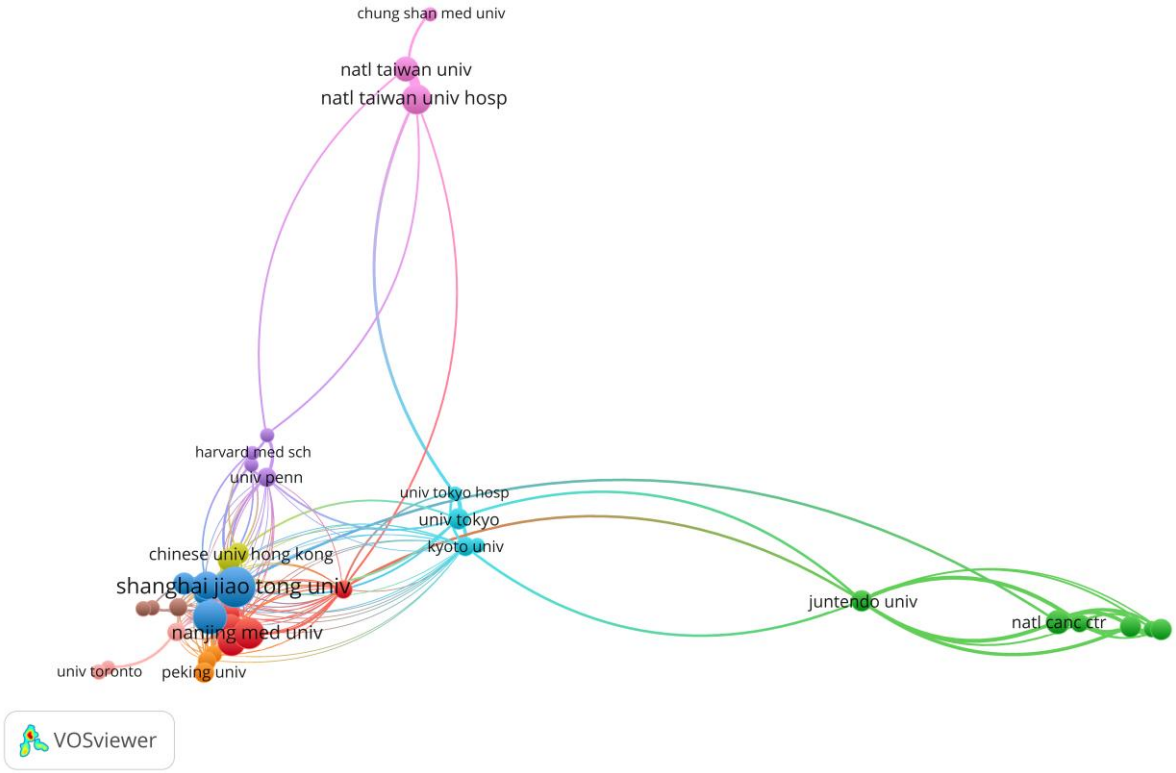


Figure 8. Institutional collaboration structure. VOSviewer included 47 organizations with at least 10 publications. Node size represents publication count, link thickness collaboration strength, and colors network clusters. Fractional counting and association-strength normalization were used.

Lowering the threshold to eight publications expanded the network to 66 organizations without altering the principal regional cores, while adding lower-frequency peripheral institutions (Supplementary Figure S4A). Detailed network statistics and threshold-sensitivity results are provided in Supplementary Table S8.

Reference co-citation structure

Finally, reference co-citation analysis characterized the intellectual base underpinning these trajectories. A fully connected set of 139 cited references met the threshold of at least 30 citations and was organized into five clusters (Figure 9). The most frequently cited anchors were Suzuki et al. (1999; 257 citations), Park et al. (2017; 203), Aberle et al. (2011; 194), Ginsberg and Rubinstein (1995; 172), and Saji et al. (2022; 140). Collectively, these anchors spanned

preoperative localization, lung-cancer screening and nodule management, and randomized evidence on the extent of resection.

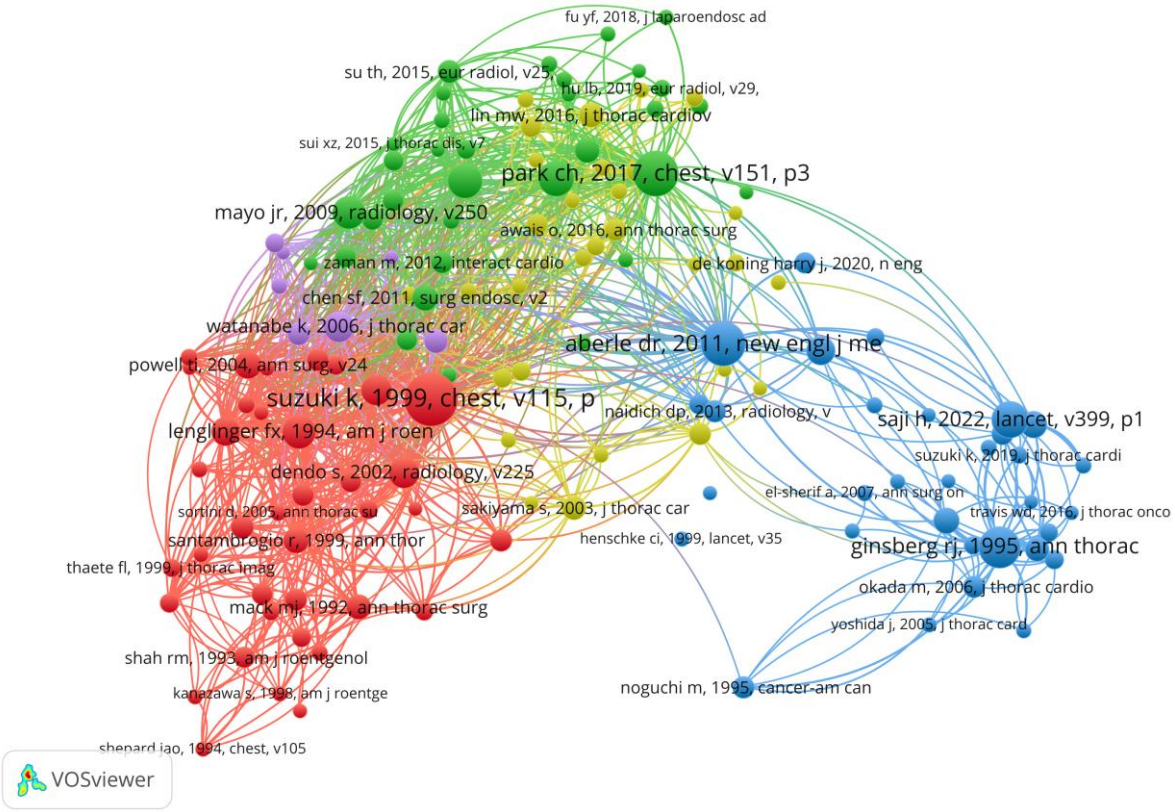


Figure 9. Reference co-citation structure. VOSviewer included 139 cited references with at least 30 citations, all in one connected component. Node size represents citation frequency, links co-citation, and colors five clusters. Full counting, association-strength normalization, clustering resolution 1.00, and the default VOSviewer layout were used.

Lowering the citation threshold from 30 to 25 expanded the network from 139 to 174 references but preserved the five-cluster macrostructure. Among the 139 references shared by both networks, total-link-strength rankings were virtually unchanged (Spearman rho = 0.998), despite limited movement of boundary references between adjacent clusters. The lower-threshold network and detailed sensitivity statistics are provided in Supplementary Figure S4C and Supplementary Table S8, respectively.

Discussion

Technological expansion and clinical evidence maturation

Taken together, these findings show that precision surgery for pulmonary nodules has expanded rapidly without an equivalent shift toward later-stage clinical evaluation. Of 1,308 included

publications, 57.6% appeared during 2020-2026; among 1,133 primary studies eligible for maturity assessment, the proportion reaching EM3-EM5 increased from 14.0% in 1995-2009 to 40.0% in 2020-2026. Yet only 39 studies (3.4%) reached EM4 (prospective controlled) or EM5 (randomized) evaluation. The principal finding is therefore a persistent gap between technological expansion and later-stage clinical evaluation.

This overall gap concealed substantial heterogeneity across technology domains. Precision resection had the most advanced maturity profile, whereas localization, navigation, minimally invasive innovation, robotic thoracic surgery, and advanced guided/integrated surgery remained distributed across earlier and later stages to varying degrees. These domains have progressed along different developmental timelines. The thematic, bibliographic-coupling, and burst analyses provide a complementary view of this transition: an older intellectual base centered on localization and conventional thoracoscopic resection has increasingly been supplemented by navigation, fluorescence, three-dimensional reconstruction, robotics, and integrated guidance.

The distinction between research visibility and evidence maturity is therefore central to interpretation. Publication momentum should not be mistaken for clinical readiness: bibliometric visibility identifies where scientific attention, citation connectivity, and collaboration are accumulating, whereas evidence maturity asks how far the underlying interventions have progressed through clinical evaluation. This divergence matters clinically because the most visible or rapidly expanding technologies are not necessarily those with the most mature comparative evidence base. The evidentiary bottleneck is therefore shifting from demonstrating technical feasibility toward establishing reproducible incremental clinical value under controlled conditions, consistent with the staged evaluation logic of the IDEAL framework [11].

These maturity patterns developed within geographically concentrated research ecosystems. Research output and collaboration clustered particularly in China, Japan, Taiwan, and North America. Because many precision-surgery technologies depend on specialized imaging, platform availability, operator experience, and coordinated perioperative workflows, broader

multicenter and cross-regional evaluation remains important for determining whether performance is reproducible beyond the technology-rich centers in which these approaches were refined. Against this broader research landscape, the domain-level trajectories help explain why evidence maturation has been uneven.

Technological expansion has outpaced evidence maturation in localization and navigation

At the domain level, the mismatch between technological growth and evidence maturation is especially apparent in localization, the earliest practical bottleneck created by thoracoscopic management of small, deep, subsolid, or otherwise nonpalpable nodules. CT-guided hook-wire and percutaneous dye strategies converted an occult radiologic lesion into an operative target, but their effectiveness was accompanied by technique-specific risks such as pneumothorax, hemorrhage, and marker displacement [17, 18]. Subsequent methods progressively changed what constituted a usable target: lipiodol made deep lesions fluoroscopically visible [19-21], microcoils provided retained internal markers and were evaluated in a prospective randomized trial [6], and VAL-MAP shifted localization from a single point toward a bronchoscopically generated map of the intended resection geometry [22, 23]. Fluorescence-guided marking broadened compatibility with minimally invasive and robotic workflows [24], while radioguided techniques [25-27] and bronchoscopically implanted RFID tags [28] further expanded signal-based and depth-aware targeting. This diversity helps explain why a large localization literature can coexist with only moderate later-stage evidence maturity: the studies do not evaluate a single stable intervention, and clinically relevant trade-offs differ across access routes, markers, timing, imaging requirements, and complication profiles.

A parallel evolution occurred in bronchoscopic navigation, which shifted targeting from transthoracic puncture toward airway-based access. Early ENB-guided dye marking demonstrated that navigation could place localization and surgery within the same procedural sequence [29, 30], and subsequent studies extended this approach to subsolid lesions, multispot mapping, and near-infrared ICG delivery [31-33]. Hybrid-operating-room CBCT then brought

image acquisition, localization, and resection into a single environment [34]. At the same time, navigation platforms evolved from virtual route guidance toward image-confirmed peripheral access. Meta-analytic evidence documents both the scale and heterogeneity of navigation bronchoscopy [35]. Robotic bronchoscopy has since emerged as another route to peripheral access, with meta-analytic evidence supporting its diagnostic performance and safety [36], while early integrated workflows have combined robotic bronchoscopy, CBCT confirmation, and ICG marking before resection [37]. The prospective multicenter CONFIRM study further demonstrated near-universal tool-in-lesion confirmation with shape-sensing robotic bronchoscopy integrated with mobile CBCT [38].

Taken together, the localization and navigation trajectories expose the central evaluative problem. Studies variously report marker visibility, localization success, diagnostic yield, tool-in-lesion confirmation, same-session completion, procedural time, radiation exposure, or complications; these outcomes describe different steps of the pathway and are not interchangeable [17, 24, 35]. At an early developmental stage, reproducible technical success is an appropriate objective. As platforms stabilize, however, the relevant question shifts to incremental clinical value: whether a strategy improves margin adequacy, reduces puncture or transfer burden, lowers complications or radiation exposure, prevents conversion, or improves patient-centered recovery relative to a contemporary standard. Without harmonized intervention definitions and endpoints, publication growth can outpace the ability to compare technologies rigorously.

Why precision resection shows a relatively advanced evidence profile

This contrast is particularly apparent in precision resection, where central clinical questions became stable enough to support progressively stronger study designs and the most advanced maturity profile (92/203, 45.3% at EM3-EM5). The 1995 Lung Cancer Study Group trial established lobectomy as the historical reference after greater recurrence with limited resection [3], but intentional parenchyma-sparing strategies continued to be refined in selected T1N0M0

disease [39] and in multicenter evaluation of radical sublobar resection for small peripheral tumors [40]. CT phenotype then became an explicit selection variable: JCOG0804/WJOG4507L supported sublobar resection for ground-glass-dominant tumors, and JCOG1211 extended prospective segmentectomy to predominantly ground-glass lesions up to 3 cm [41, 42]. Thus, the evidence pathway evolved from whether less lung could be removed to which patients and tumors could undergo parenchymal preservation without compromising oncologic control.

As the clinical question became more stable, randomized trials provided the decisive benchmark. JCOG0802/WJOG4607L showed superior overall survival after segmentectomy in a defined population of small peripheral NSCLC while also demonstrating a higher local relapse rate, keeping technical quality and local control central to interpretation [4]. CALGB/Alliance 140503 independently established noninferiority of sublobar resection for disease-free survival in carefully staged peripheral node-negative tumors [5]. A post hoc analysis subsequently found broadly similar survival across lobectomy, segmentectomy, and wedge resection within the trial population, although wedge and segmentectomy were not randomized directly against each other [43]. Contemporary consensus has therefore shifted toward the features that make parenchymal preservation oncologically sound: patient selection, anatomical planning, adequate margins, nodal evaluation, and readiness to extend resection when required [44]. Consistent with that shift, a supplementary JCOG0802 analysis linked locoregional relapse to factors including pure-solid appearance and insufficient margin distance [45].

This stabilization of populations, comparators, and oncologic endpoints helps explain why precision resection matured further than several device-dependent domains. Even here, however, late-stage evidence remains selective; only 3 of 203 precision-resection studies were classified as EM5, and the major randomized trials apply to defined tumor sizes, radiologic phenotypes, nodal conditions, and operative strategies. The next phase should therefore address unresolved decisions within an already validated sublobar framework: when wedge resection is sufficient, how margin requirements should vary with tumor phenotype and location, how nodal

assessment should be standardized, and whether added planning or guidance technologies produce measurable incremental benefit.

Emerging technologies and integrated workflows: convergence without uniform maturity

If precision resection illustrates how stable clinical questions enable later-stage evaluation, the newer technology domains illustrate the opposite challenge: innovation is increasingly distributed across access, execution, planning, and intraoperative guidance. Minimally invasive innovation initially focused on reducing the access burden of precision resection: uniportal and subxiphoid approaches extended increasingly complex anatomical segmentectomy to reduced-port platforms [46, 47], while non-intubated and tubeless strategies sought to reduce anesthetic and postoperative device burden [48, 49]. ENB-guided ICG localization has also been combined with non-intubated uniportal VATS in a single operating environment [50]. These approaches broaden the meaning of precision from the amount of lung removed to the burden imposed by the entire intervention, but their endpoints range from pain and length of stay to technical completion and workflow efficiency, contributing to a relatively dispersed maturity profile.

Within this broader shift, robotic thoracic surgery illustrates the transition from feasibility to comparative value. Early reports established the technical feasibility of robotic anatomical segmentectomy [51, 52]. Once the procedure became standardized, VATS became the relevant comparator: a multi-institutional propensity-matched analysis found broadly similar operative and postoperative outcomes between robotic and thoracoscopic segmentectomy, with higher cost but greater N1 nodal retrieval in the robotic group [53], and contemporary database analyses confirm the broader migration of segmentectomy toward minimally invasive and robotic approaches [10, 54]. A recent meta-analysis of propensity-matched studies likewise found broadly similar perioperative, nodal, and reconstructed survival outcomes [55]. These findings illustrate why adoption should not be equated with evidentiary maturity. Robotic surgical execution and robotic bronchoscopy also occupy different steps of the pathway: resection versus

endoluminal access and targeting, even when both platforms are used sequentially in the same patient.

The same tension between technical sophistication and incremental value is evident in three-dimensional planning. Three-dimensional CT angiography, bronchography, virtual safety-margin planning, and patient-specific virtual segmentectomy progressively shifted imaging from diagnosis toward operative design [56-58]. Yet the multicenter DRIVATS randomized trial did not show shorter operative time or broad perioperative improvement with preoperative three-dimensional reconstruction compared with standard CT [59], despite pooled evidence suggesting benefits for selected planning, margin, or perioperative outcomes [60]. The implication is not that better visualization lacks value, but that its benefit depends on whether it changes a difficult anatomical decision or improves resection geometry in a measurable way.

Intraoperative guidance technologies show a similar progression from feasibility toward increasingly specific clinical questions. Intravenous ICG enabled intraoperative delineation of intersegmental planes [61, 62], and subsequent systematic and comparative evidence supported its reproducible use as an adjunct to video- or robot-assisted segmentectomy while clarifying differences from conventional inflation-deflation methods [63-65]. Augmented-reality localization progressed rapidly: an initial randomized noninferiority trial demonstrated comparable localization and resection success with less procedural burden [66], a prospective multicenter study supported cross-institutional feasibility and safety [67], and 2026 randomized trials reported lower radiation exposure, shorter localization pathways, or greater targeting precision [68, 69]. Tumor-targeted molecular imaging extends this logic beyond anatomy: folate-receptor-targeted fluorescence improved localization of selected ground-glass lesions and was adapted to robotic pulmonary resection [70, 71], while the multicenter phase III ELUCIDATE trial showed that pafolacianine could reveal clinically significant information not available from conventional white-light visualization and palpation [72].

Taken together, these developments help explain why the most recent thematic and burst signals cluster around three-dimensional reconstruction, localization, fluorescence, robotics, and integrated guidance while evidence maturity remains uneven. The unit of innovation is shifting from the individual device to the integrated surgical pathway. A contemporary workflow may combine three-dimensional planning, bronchoscopic or robotic navigation, CBCT confirmation, fluorescence marking or plane identification, and minimally invasive or robotic resection within a single encounter [34, 37, 50]. Evaluating such pathways requires both conventional surgical outcomes and pathway-level measures such as the number of procedural encounters and transfers, target confirmation, procedural burden, conversion, and resource use. As components are combined, the main bottleneck increasingly becomes evaluability: the pathway must be sufficiently standardized to determine which components are necessary, which are redundant, and whether the net clinical gain justifies added complexity.

Clinical translation and future research priorities

Across these domains, a common translational principle emerges: evaluation should be matched to developmental stage. Early platforms should first establish multicenter reproducibility, technical failure modes, learning curves, and predefined safety outcomes. Once the intervention, operator requirements, and workflow are sufficiently stable, prospective comparative studies should test whether technical success translates into clinically meaningful benefit. Randomized evaluation becomes most informative when equipoise, standardization, and trial feasibility are present. This stage-matched approach follows the logic of IDEAL and avoids applying the same evidentiary expectation to an early prototype and an established surgical strategy [11].

One immediate operational priority is outcome standardization across technology domains. Future protocols should distinguish technical success from clinical benefit and prespecify intervention-appropriate endpoints, including target acquisition, failure or conversion, margin adequacy, clinically relevant complications, radiation exposure, procedural efficiency, repeat procedures, hospital utilization, recurrence when applicable, and patient-reported recovery. This

is particularly important for localization, navigation, and image-guided interventions, where apparently similar studies still use heterogeneous definitions of success and failure [17, 24, 35]. Common definitions would make between-technology comparisons more interpretable and reduce the risk that measurement choices are mistaken for differences in clinical performance.

The appropriate comparator, however, should reflect the maturity of the underlying surgical strategy. For precision resection, randomized trials have already established selected sublobar strategies as contemporary oncologic standards [4, 5]. New planning, localization, fluorescence, or robotic technologies should therefore be tested against a well-executed modern pathway and asked to demonstrate incremental value for patient selection, margin control, nodal assessment, perioperative efficiency, function, or long-term outcome [44, 59, 60]. For robotic and other resource-intensive platforms, value assessment should also include cost, access, institutional volume, learning curve, workflow efficiency, and implementation sustainability [10, 55]. Prospective registries can complement controlled trials by capturing iteration, rare complications, and post-adoption performance, but should not substitute for comparative designs when the question is incremental patient benefit.

Taken together, these priorities suggest that the next phase of precision surgery should be defined less by the introduction of additional platforms than by evidence showing which technologies add measurable value to an increasingly precise standard of care. Studies should state the developmental stage of the intervention, define the comparator and operator requirements, and prespecify clinically meaningful outcomes. Doing so would make technical novelty, workflow improvement, and patient benefit distinguishable endpoints rather than interchangeable claims of progress.

Strengths and limitations

A principal strength of this study is the explicit separation of research visibility from clinical evidence maturity within a single analytical framework. Bibliometric and network analyses identify where research activity is concentrated and how the literature is thematically and

intellectually connected, whereas the EM0-EM5 framework addresses a different question: how far eligible primary studies have progressed through clinical evaluation. This separation reduces the risk of treating publication volume, citation prominence, or keyword activity as proxies for clinical readiness. Structured technology-domain classification and clinical contextualization then connect these complementary layers to the operative pathways they represent; VOSviewer and CiteSpace were used for network structure and temporal research-front analysis [14, 15].

A second strength is the use of analysis-specific definitions and denominators rather than forcing heterogeneous outputs onto a single study base. Country contribution, collaboration networks, Author Keyword themes (K1-K9), bibliographic-coupling communities (R1-R6), technology domains, and evidence maturity were each analyzed according to their own operational criteria and eligible study sets. Technology domains were non-mutually exclusive, whereas ordered evidence-maturity analyses were restricted to eligible primary studies; clinical contextualization then linked these layers without treating them as interchangeable. Prespecified thresholds and sensitivity analyses supported reproducibility of the network procedures [14, 15].

Several limitations remain. First, the bibliometric analysis was based on the Web of Science Core Collection and restricted to English-language publications classified as Article or Review Article. Because major bibliographic databases differ in journal coverage, citation capture, and search functionality [73], and systematic differences in language and journal representation have been documented [74], the present results describe the WoSCC-indexed English-language research landscape rather than the entirety of global scholarship. Regional, non-English, or incompletely indexed work may therefore be underrepresented. Evolving terminology and newly introduced platform names may also have limited retrieval of some relevant publications despite the broad predefined search strategy.

Second, the clinical contextualization was narrative and milestone-oriented rather than an exhaustive systematic review or formal comparative assessment of treatment effects. Representative landmark, clinical, comparative, and emerging-technology publications were

used to place the bibliometric patterns in surgical context, and contextual references outside the quantitative corpus did not contribute to publication counts, network analyses, technology-domain distributions, or evidence-maturity calculations. This component should be interpreted as clinical contextualization rather than as a source of pooled treatment-effect estimates.

Third, bibliometric visibility is time dependent. The search was conducted on August 27, 2026, so 2026 remained an incomplete observation year and bursts extending to 2026 indicate activity at the database cutoff rather than persistence through the full calendar year. Older publications have had more time to accumulate citations, and citation impact varies with publication age, database coverage, and field-specific practices [75]. The bibliographic-coupling threshold of at least 25 global citations consequently favors established literature and may underrepresent recently published or less-cited work. Keyword networks are also threshold dependent, and citation bursts identify unusually rapid increases in attention rather than clinical superiority [14, 15].

Fourth, technology-domain and evidence-maturity classifications retain an element of interpretive judgment despite prespecified operational criteria and independent review. Contemporary precision-surgery studies often span several components of an integrated workflow; multi-membership across technology domains was therefore intentional rather than a classification defect. The EM0-EM5 framework describes progression from technical development through increasingly comparative forms of clinical evaluation. A higher EM stage should not be interpreted as lower risk of bias, greater certainty of evidence, or superior treatment effect, consistent with the distinction between developmental stage and evidentiary quality in surgical-innovation frameworks such as IDEAL [11].

Finally, different analyses were based on analysis-specific eligible study sets and attribution rules. Country profiles included publications with assignable harmonized country information, whereas the VOSviewer country co-authorship network used its own bibliographic parsing; evidence-maturity analyses included only eligible primary studies, and bibliographic-coupling

communities were derived from a citation-thresholded subset. Results from these layers should therefore be interpreted within their respective study bases rather than compared as though they arose from a single common population of publications. This analytical specificity improves interpretability but limits direct comparisons across analytical layers.

Conclusions

Precision surgery for pulmonary nodules has evolved from isolated localization and resection techniques toward integrated pathways combining lesion targeting, patient-specific anatomical planning, image guidance, minimally invasive or robotic execution, and parenchyma-sparing resection. Clinical evaluation has advanced alongside this technological expansion, but maturation remains uneven: only 39 of 1,133 eligible primary studies (3.4%) reached prospective controlled or randomized evaluation (EM4-EM5). Precision resection showed the most advanced maturity profile, whereas several newer image-guided, navigational, and platform-based strategies remain at earlier stages of clinical evaluation.

Accordingly, publication growth and technical integration should not be interpreted as equivalent to clinical readiness. Future evaluation should be matched to developmental stage and prioritize multicenter prospective comparisons, standardized clinically meaningful endpoints, and implementation assessment to determine whether new technologies add reproducible value within contemporary surgical pathways.

List of abbreviations

AR, augmented reality; CBCT, cone-beam computed tomography; CT, computed tomography; DOI, digital object identifier; EM, evidence maturity; ENB, electromagnetic navigation bronchoscopy; GGO, ground-glass opacity; GGN, ground-glass nodule; ICG, indocyanine green; IDEAL, Idea, Development, Exploration, Assessment, Long-term study; LDCT, low-dose computed tomography; MIS, minimally invasive surgery; NSCLC, non-small cell lung cancer;

RFID, radiofrequency identification; VAL-MAP, virtual-assisted lung mapping; VATS, video-assisted thoracic surgery; WoSCC, Web of Science Core Collection.

Declarations

Ethics approval and consent to participate

Not applicable. This study analyzed bibliographic records and published literature only and did not involve human participants, human data or tissue, animals, or identifiable individual-level data.

Consent for publication

Not applicable.

Availability of data and materials

The complete search strategy, analytical definitions, and reporting details are provided in the manuscript and Additional file 1. The complete cited-reference burst results are provided in Additional file 3. Derived analytical datasets, technology-domain classifications, evidence-maturity assignments, and analysis provenance supporting the findings are available from the corresponding author on reasonable request. Raw Web of Science Core Collection bibliographic records are subject to Clarivate licensing terms and are not redistributed publicly.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

JW conceived and designed the study. SZ collected and assembled the data and performed the data analysis and interpretation. JW, LX, SZ, XD, and YG contributed to drafting or revising the manuscript. All authors read and approved the final manuscript.

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Additional files

Additional file 1 (.docx): Supplementary Material. Supplementary Figures S1-S5 and Supplementary Tables S1-S6 and S8, including eligibility criteria, technology-domain and evidence-maturity definitions, country profiles, keyword and bibliographic-coupling analyses, and network-threshold sensitivity analyses.

Additional file 2 (.docx): BIBLIO Reporting Checklist. Completed 20-item BIBLIO reporting checklist with manuscript-specific locations and reporting notes.

Additional file 3 (.docx): Supplementary Table S7. Complete cited-reference burst results (237 records) and cited-reference label-normalization notes.

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