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Consensus for Operating Room Multimodal Data Management: Identifying Research Priorities for Data-Driven Surgery

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Introduction: This study aimed to identify research areas that demand attention in multimodal data-driven surgery for improving data management in minimally invasive surgery.

Background: New surgical procedures, high-tech equipment, and digital tools are increasingly being introduced, potentially benefiting patients and surgical teams. These innovations have resulted in operating rooms evolving into data-rich environments, which, in turn, requires a thorough understanding of the data pipeline for improved and more intelligent real-time data usage. As this new domain is vast, it is necessary to identify where efforts should be focused on developing seamless and practical data usage.

Methods: A modified electronic Delphi approach was used; 53 investigators were divided into the following groups: a research group (n=9) for problem identification and a narrative literature review, a medical and technical expert group (n=14) for validation, and an invited panel (n=30) for two electronic survey rounds. Round 1 focused on a consensus regarding bottlenecks in surgical data science areas and research gaps, while round 2 prioritized the statements from round 1, and a roadmap was created based on the identified essential and very important research gaps.

Results: Consensus panelists have identified key research areas, including digitizing operating room (OR) activities, improving data streaming through advanced technologies, uniform protocols for handling multimodal data, and integrating AI for efficiency and safety. The roadmap prioritizes standardizing OR data formats, integrating OR data with patient information, ensuring regulatory compliance, standardizing surgical AI models, and securing data transfers in the next generation of wireless networks.

Conclusions: This work is an international expert consensus regarding the current issues and key research targets in the promising field of data-driven surgery, highlighting the research needs of many operating room stakeholders with the aim of facilitating the implementation of novel patient care strategies in minimally invasive surgery.

Keywords: data-driven surgery, digital surgery, machine learning in surgery, surgical data management, surgical data science

INTRODUCTION

The adoption of innovative approaches such as minimally invasive, image-guided, and robotic surgery has brought the surgical domain into an unprecedented digital dimension. The result is a change in the traditional operating room into a dynamic, data-rich environment that is uniquely amenable to the development and application of artificial intelligence (AI) tools.[1]

An upcoming challenge is the ability to move beyond unimodal tasks limited to electronic health record data and images, among other sources, and expand capabilities to include a comprehensive surgical understanding via ambiance video, environmental sensors, text, speech, physiological parameters via wearables and sensors, and tabular data from surgical instruments and devices grouping several data input modes, laying the groundwork for multimodal data AI applications. In a surgical context, multimodal AI refers to models seamlessly integrating diverse data formats, both during the training phase and when presented with real-time inputs before, during, and after surgical procedures.[2] These flexible capabilities have led to the implementation of multimodal data AI applications across diverse

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medical domains,[3,4] having the potential to drive a wide array of perioperative data-driven applications for surgery.[5]

Within this context, the need to capture, manipulate, store, transfer, and seamlessly use data sourced from patients, instruments, equipment, and surgical teams has emerged. The introduction of digitized solutions into surgical practice and the as-of-yet-unknown impact it will have on patient care present inherent research challenges and opportunities. As part of a Franco-German research project titled 5G-operating room (OR), this study was designed to identify via an electronic Delphi (e-Delphi) methodology, an expert consensus on important research areas that demand attention in the field of multimodal data-driven surgery. A secondary aim was to outline a strategic roadmap for the enhancement of data management in the field of minimally invasive surgery (MIS). Research gaps' identification via an expert consensus panel highlights areas that may help integrate digitized solutions into surgery and organize novel methods for real-time data use. At the same time, the findings may provide guidance to healthcare practitioners, researchers, and medical industry stakeholders interested in leveraging surgical data science effectively for patient benefits.

MATERIALS AND METHODS

e-Delphi Consensus Research Strategy

This study was designed to gather collective intelligence from multidisciplinary experts in the fields of surgery, anesthesiology, engineering, and surgical data science through a modified e-Delphi methodology, which is considered a highly structured communication approach that relies on expert panelists to arrive at a consensus through iterative rounds.[3,6]

The e-Delphi methodology uses unbiased interactions between participants via electronic questionnaires rather than face-to-face communication, with the aim of preserving participant anonymity. Each panelist received a personal invitation through email and communicated with consensus coordinators only.

Throughout the consensus process, conflict-of-interest policies were guided by principles of proportionality, transparency, accountability, and fairness, focusing on highlighting data-driven surgery research priorities.[7] The research strategy of this study involved 3 phases: problem identification, narrative literature research, and online surveys (validation and 2 modified e-Delphi rounds).

The problem identification phase was performed by a research group (n=9; names listed in acknowledgment) formed by senior surgical and computer science researchers who held a day-long brainstorming session (April 2022) to define search terms relevant to the objectives of the study. The same group acting as a focus group then used the identified terms and topics, performed a narrative literature review, discussed the findings, and generated statements that were later used during the consensus process. The principle was to distinguish between those who provided evidence and those who voted on the statements' recommendations.

For the statement's generation process, research members were distributed into 5 categories of research according to the pipeline stages of data management, a curated database of research manuscripts was then reviewed, the findings were compiled using an online summary of findings tables, and the final statement phrases were extracted and grouped in categories to create a list for the first round of the surveys.

The third phase of online surveys began with a review and validation of the above described by a panel of renowned medical and technical experts (n=14, names listed in acknowledgment) via an organized electronic survey using a 5-point Likert scale (1=completely disagree, 2=disagree, 3=neutral, 4=agree, and 5=completely agree), the recruitment followed the criteria: (1) renowned experts were distinguished through their active participation in translational research projects pertinent to the field, alongside their senior authorship of academic peer-reviewed publications in surgical data science and surgical innovation that they represent a comprehensive but not exhaustive list of experts in the field and (2) involvement in data science consensus projects. The renowned expert group validated with >70% of the agreement the categorization and statements proposed by the research group. Finally, there were two rounds of electronic surveys by an invited consensus panel (panel size n=30, names listed in acknowledgment) whose members were selected by objective and predefined criteria: (1) panelists were defined[8] as individuals with expertise and experience in healthcare data, medical engineering, and artificial intelligence as applied to the surgical and anesthesiology domains, as evidenced by their relevant peer-reviewed publications in the field; (2) diverse representation of members from different specialties to achieve homogeneity; (3) geographical distribution; and (4) experts recommended by the other committee members (snowballing technique).

The aim of Delphi Round 1 was to reach a consensus on the importance of each statement relevant to current issues and research gaps in surgical data science using a 5-point Likert scale (1=completely disagree, 2=disagree, 3=neutral, 4=agree, and 5=completely agree). The results were reassessed, eliminating statements with mean scores <4. The remaining statements were again grouped according to previously predefined broad categories and ordered by the level of agreement.

Delphi round 2 focused on ranking the statements from round 1 in order of importance using a Likert scale (1=not important, 2=somewhat important, 3=moderately important, 4=very important, and 5=essential) and eliminating statements with mean scores <4. The resulting statements were then organized according to their level of importance within each of their predefined categories.

Therefore, the final conclusions and key outcomes of the Delphi method were based on the top-ranked statements from each category, following both Delphi rounds. Finally, a roadmap was proposed using research gaps considered essential and very important.

Panelists were given two weeks to answer, with a subsequent rereminder and 1-week extension, and the results of each round were reviewed, analyzed, and reorganized to build the content of consecutive rounds (Fig. 1).

Statistics

In rounds 1 and 2, a descriptive analysis with means and standard deviation scores was used, which were arranged in descending order to indicate a high ranking. Statistical analyses were performed using IBM SPSS Statistics 25.0 (SPSS, Chicago, IL, US).

RESULTS

Phase 1: Problem Identification

The result of the in-person brainstorming session was the identification of a list of defined terms related to surgical data management (surgical data science, artificial intelligence in surgery, artificial intelligence in anesthesiology, digital surgery, machine learning in surgery, surgical data recording systems, and precise surgery), with the objective of using these terms to perform the narrative literature review.

Phase 2: Narrative Literature Review

Using an AI-powered research engine (Researchrabbit.ai, Seattle, WA), the keywords previously generated were employed to perform a search within the PubMed and semantic scholar databases, the advantage of which is that it has access not only to conventional publications but also to conference papers and abstracts relevant to this new domain.

In total, 558 papers were identified followed by keyword input; through consideration of titles and abstracts, a curated

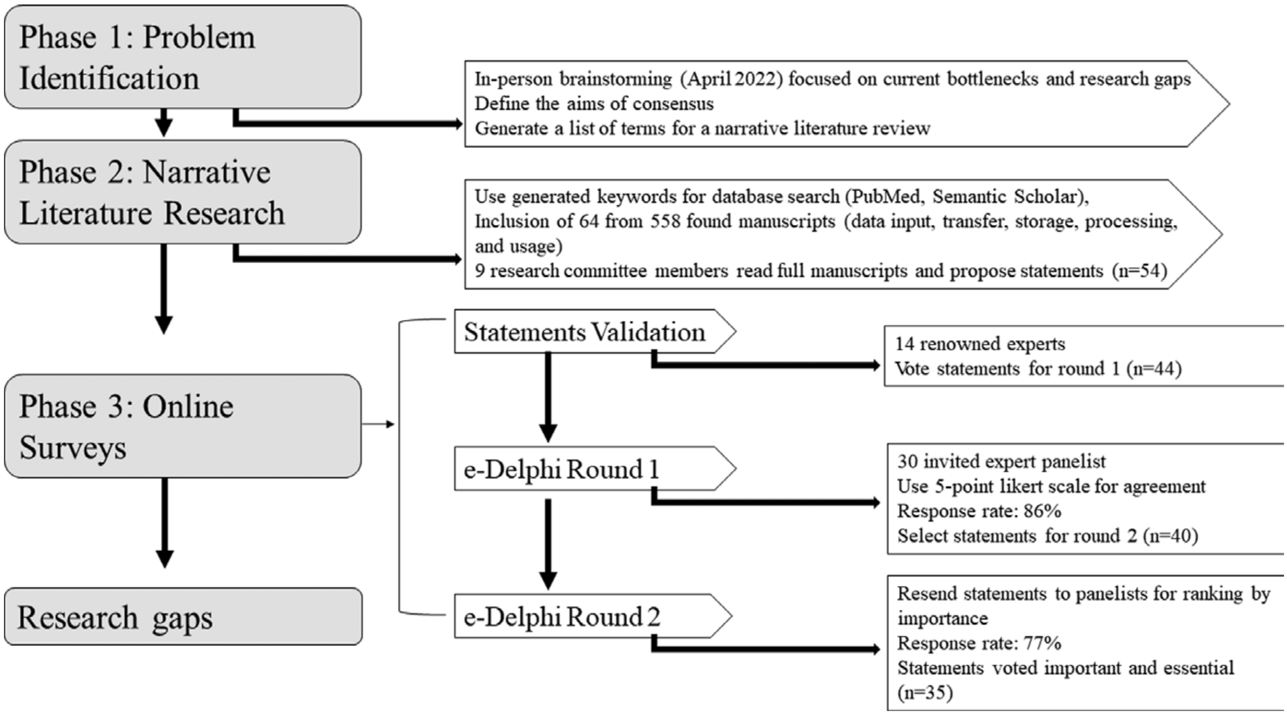

FIGURE 1. Consensus methodology flowchart.

list of 64 non-exhaustive manuscripts was found suitable for inclusion. These manuscripts underwent categorization based on their titles and abstract content into 5 categories according to stages of the data pipeline management from input to usage: (data input, transfer, storage, processing, and usage).

In the second step, the research committee members read the full contents of all papers, wrapped up their findings in an online summary of finding tables, and proposed an initial list of statements for each category. In addition, the reading identified an additional group of content describing research needs in the field; the group, therefore, added a sixth category of research gaps for these statements (Fig. 2). The number of statements grouped into 5 categories was 54 and can be found in Annex 1 (http://links.lww.com/AOSO/A372).

Phase 3: Online Surveys

Statements' Validation

The renowned expert committee evaluated and provided feedback on the categories and preliminary statement list generated by the research committee via an organized electronic

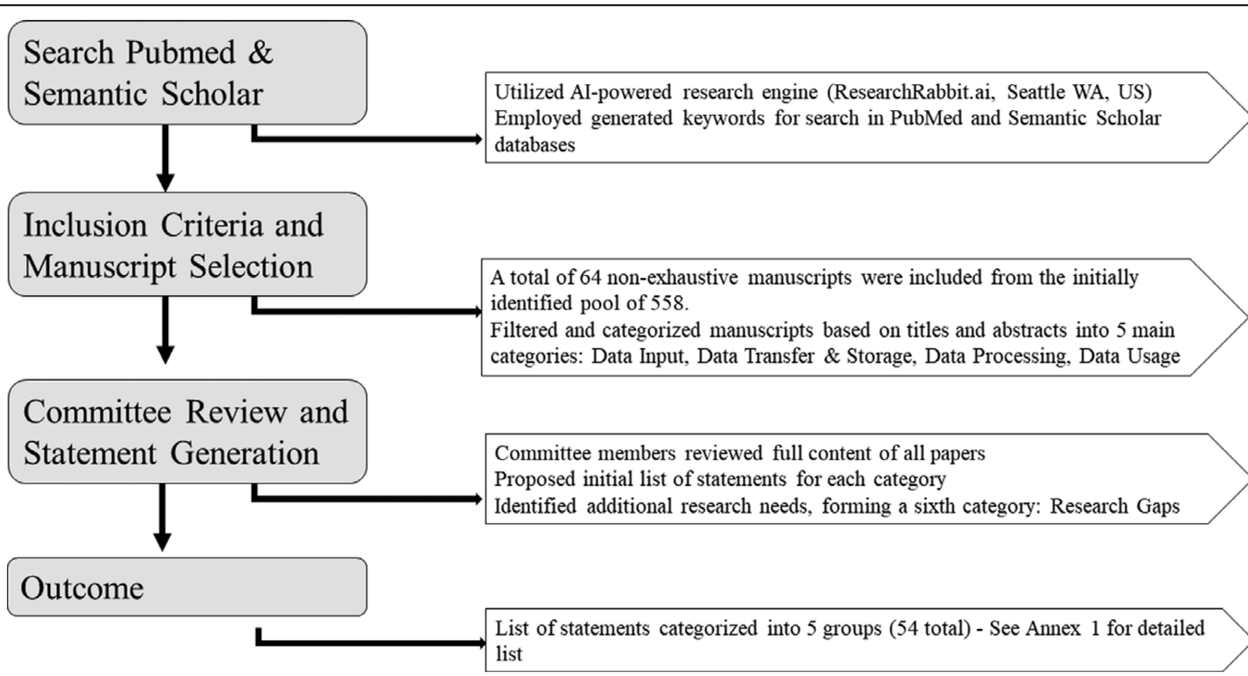

FIGURE 2. Narrative literature review flowchart.

TABLE.

Statements Categorized and Ranked by Importance by Consensus Panelists

Category 1: operating room data input
The integration of various equipment such as surgical instruments, anesthesia workstations, laparoscopic cameras, and others aids in collecting high-dimensional data to ensure optimal patient outcomes.
Surgical video endoscopy is a valuable source of intraoperative data that can assist in the evaluation and assessment of surgical procedures.
The success of context awareness in surgery relies on receiving inputs from various sources, primarily the human senses, with a particular emphasis on visual feedback.
The integration of multimodal data obtained from various devices within the operating room is critical in shaping context awareness and plays a crucial role in the development of multimodal deep learning/machine learning models.
OR activities can be captured digitally either through interactions with equipment, such as information systems, room control interfaces, imaging devices, and instruments.
Categories 2 and 3: operating room data transfer and storage
Data streaming is necessary to enable real-time inference within the OR; thus, the hardware and networks receiving these streams must be sufficiently fast to decode the streams with minimal latency and high reliability.
Effective transfer of data from the preoperative setting, such as CT scans, into the operating room environment to facilitate informed decision-making during surgery.
Safe and reliable human-perceived real-time communication is necessary for surgical applications; this can be achieved with sufficient bandwidth and low latency.
Data preprocessing may be a good way to address the massive data storage burden.
OR data are mainly locally stored in a data center; compression of videos is necessary to decrease storage needs as storage remains a burden nowadays.
Category 4: operating room data processing
The acquisition, recording, and processing of data streams in the OR need to be standardized to enable the usage of high-volume or multimodal data.
Surgical videos (endoscopes and microscopes) can provide information for image-based analysis and can be integrated with data from other sensors to create detailed models.
To facilitate data analysis, a consistent, hierarchical, and extensible data format with semantic interoperability across institutions should be created.
The methods of data analysis, modeling, and processing need to accommodate the heterogeneity of highly multimodal OR data streams and of highly varying interventions and workflows.
High-speed wireless communication technologies, such as 5G, enable multimodal inference.
Category 5: operating room data usage
Monitoring OR and surgical activities to prevent “never” events such as wrong-site surgery
Monitoring OR activities to improve OR management
Using AI-enhanced intraoperative imaging features such as image fusion and fluorescence
Using AI-based perioperative alarms to automatically assess a patient’s vital signs and surgical video data to prevent major complications and death within 30 days after surgery, thereby enhancing surgical decision-making
Monitoring surgical activities in the OR to improve anesthesia timings
Category 6: recognized research gaps
Definition of standard formats for recording and storing data must be defined to ensure compliance with privacy and data protection regulations.
Linking multidimensional OR data with patients’ data to identify common errors impacting outcomes and develop quality improvement interventions.
Complying with patient-related data protection act regulations by operating room stakeholders, such as GDPR, HIPAA, and the NHS 2018 Act.
Achieving format standardization of AI models to improve interoperability and model sharing
Addressing data transfer security within the context of a private 5G operating room network

GDPR indicates General Data Protection Regulation; HIPAA, Health Insurance Portability and Accountability Act; NHS, National Health Service.

survey; after the evaluation of the expert committee, 5 statements were removed due to agreement of <70%. In addition, 5 statements were identified as containing duplicate content. The final list of organized statements for the first round of the Delphi was 44.

Outcomes of the e-Delphi Round 1

A curated list of 44 statements organized into six categories was electronically sent to the invited expert panel. Twenty-six of 30 experts answered the survey (response rate, 86%); 40 of 44 statements were rated 4=agree and 5=completely agree on a 5-point Likert scale. The 44 full statement lists, including the four statements dropped, can be found in Annex 2 (http://links.lww.com/AOSO/A373).

Outcomes of the e-Delphi Round 2

The 40 statements from round 1 were resent to the panelists asking them to rank each statement within its associated category using a 5-point Likert scale as to their importance as research priorities. The response rate in the final round was 77%, and 35 of the 40 statements were voted as very important or essential. The 35 grouped statements including the 5 dropped from the list, can be found in Annex 3 (http://links.lww.com/AOSO/A374). To conclude, a thematic analysis conducted by a focus group (A.G., A.H., J.V., and L.S.) was employed to facilitate the identification of key findings included in the discussion and the formulation of the final consensus statements, providing a comprehensive output for the consensus process. (Table—statements categorized and ranked by importance by consensus panelists). Additionally, a research priority roadmap based on the research gaps voted as essential and very important is presented.

DISCUSSION

The digitalization of operating rooms has the potential to enhance patient safety and outcomes. However, the exponential increase in data generated by the expanding use of digital technologies in surgery introduces new complexities and unknowns. Effectively managing these data requires a careful filtration process to extract pertinent information that can drive decision-making, which requires a clear understanding and standardization of data management procedures.

This paper presents a consensus by leading experts in this promising “new frontier” of surgical care; the main outcomes according to most-agreed upon statements by the international expert panel are described as follows, In category 1 (data input), panelists found the integration of a diverse array of equipment in a network; namely, surgical instruments, anesthesia workstations, and laparoscopic and environmental cameras may convert the OR into a hub for collecting high-dimensional data. This integration may enable a holistic understanding of the surgical procedures by digitizing the entire operating room. (essential, 56.5%; very important, 43.5%).

In categories 2 and 3 (data transfer and storage), the significance of data streaming within the OR is highlighted, emphasizing the importance of real-time decision support. Rapid and informed decisions during surgical intervention depend on the availability of real-time information. To this end, the hardware and networks responsible for receiving and analyzing these data streams should display high-performance capabilities such as speed, reliability, security, and minimal latency in decoding the information they carry (essential, 60.9%; very important, 30.4%),

In category 4 (data processing), standardization of data streams within the OR was considered essential and very important by 100% of the panelists, as it was felt to be a key factor in advancing surgical practices. The seamless acquisition, recording, and processing of data streams within the OR environment may play a key role in unlocking the potential of high-volume and multimodal data, while simultaneously ensuring standardization of formats for recording and storing data in compliance with strict privacy and data protection regulations highlights the ethical and legal dimensions of managing these data streams.

Image-based data analysis from surgical videos and sensors, obtained from "endoscopes and microscopes,", was rated as essential and very important by 91% of the respondents. These videos may provide invaluable image-based insights that, when integrated with data from other sensors, create comprehensive and detailed models.

Key Outcomes in Category 5 (Data Usage): Our panelists emphasized the role of "AI-driven support in monitoring operating room activities," which aligns with previous initiatives to implement surgical data recording technology.[9] This approach depends on deploying video input sources that can track interactions between surgical teams, equipment, and patients, which is a somewhat controversial proposal, owing to privacy concerns. The primary aim is to provide automatic feedback, either real time or post hoc, which might be a proactive measure that could help avert common preventable errors. In addition to visual data, the integration of multimodal data sources, specifically numeric data derived from the anesthesia workstation (gas delivery scavenging system, vaporizers, electronic flow meters, ventilator, and monitors), alongside data originating from endoscopic towers (light source, camera system, video monitor, endoscope, insufflator, suction, and irrigation systems), surgical robotics, table controls, and electrosurgical units (generator and handpiece), would provide a rich source of information to improve patient outcomes by designing AI algorithms that could provide an unprecedented understanding of the ongoing surgical procedure and lead to safer, more comprehensive decision-making.[10,11] This emphasizes that the key outcomes can be applied to the field of MIS, where endoscopic video, whether rigid or flexible, is considered a main source of data input by expert panelists.

Currently, operating room equipment generates information in a multitude of separate formats and lacks synchronization and network cohesion. Currently, multimodal data synchronization is limited owing to the limited interoperability between systems.[12] Thus, an important step toward digitalization may involve the integration of all devices into a unified network, facilitating standardization and interoperability among medical facilities.[13] The shear density of data in today's ORs amplifies the challenge of data storage, demanding strategic approaches to identifying essential data to mitigate storage constraints. Latency issues also impede the real-time use of data; edge processing within the OR along with high-capacity transmission capabilities might solve latency issues and augment real-time or near-real-time decision support and perhaps high-bandwidth technologies, such as autonomous capabilities in robotics. In practical terms, one might consider a surgical setting where real-time data stream wirelessly from various devices such as monitors, cameras, and robotic assistants and are integrated into a single network where, through predetermined intelligent filtering, critical information, such as devices and patient status, is immediately accessible to the surgical team, empowering them to make well-informed decisions in real time.

The expert consensus panel prioritized key research gaps for operating room data management including the establishment of standard formats for recording and storing data to ensure compliance with privacy regulations, such as General Data Protection Regulation, Health Insurance Portability and Accountability Act, and the National Health Service 2018 Act (eg, implementing systems for documenting and storing patient information during surgical procedures). Efforts should target linking multidimensional operating room data with patient data to identify common errors during surgery (eg, correlating surgical outcomes with intraoperative patient and surgical equipment data). Additional initiatives may include standardizing AI model formats to enhance interoperability and facilitate sharing (eg, creating a standardized framework for training and deploying surgical AI algorithms). Future research should address ensuring secure data transfer within a private 5G operating room network (eg, safeguarding patients' data during its utilization.). These statements, endorsed by the panelists, aim to advance data management practices and research in the field.

The weaknesses of this study include the relative paucity of peer-reviewed source materials, owing to the newness of the field, which may have restricted the number of research topics identified, although over 40 topics were verified by our expert panel. In addition, the Delphi process used was somewhat different from the classic multiple-iteration format but seemed suitable for our goal of identifying and prioritizing research topics. Our relatively small panel of Delphi experts (30) again reflects the relative newness of medical computer science and our specific focus on OR data.

CONCLUSIONS

This work is an international expert consensus regarding the current issues and key research targets in the promising field of data-driven surgery, highlighting the research needs of many operating room stakeholders with the aim of facilitating the implementation of novel patient care strategies in MIS.

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APPENDIX

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