Augmented Reality in Minimally Invasive Surgery Procedures

Subjects: Surgery | Engineering, Biomedical

Contributor: Phillipp Brockmeyer, Bernhard Wiechens, Henning Schliephake

Augmented reality (AR) technology is gaining increasing interest in the development of minimally invasive surgery (MIS) procedures. The main application areas can be divided into three main groups: Navigation, education and training, and user-environment interfaces. Although AR-guided navigation systems do not yet offer a precision advantage, benefits include improved ergonomics and visualization, as well as reduced surgical time and blood loss. Benefits are also seen in improved education and training conditions and improved user environment interfaces, which may indirectly influence MIS procedures. Controlled studies with large case numbers and standardized outcome parameters and reporting are lacking to confirm the added value for clinical use.

Keywords: augmented reality (AR) ; virtual reality (VR) ; mixed reality (MR) ; minimal invasive surgery (MIS)

1. Advantages and Disadvantages of Minimally Invasive Surgery (MIS)

Advances in surgery have the potential to significantly improve patient outcomes and reduce hospital length of stay (LOS) [1]. Healthcare providers can achieve cost savings and improve efficiency in the delivery of healthcare services, and increase the capacity to treat more patients, thereby improving access to care and reducing waiting times [2]. To achieve these goals, it has been emphasized to continue to invest in surgical advances and technologies, such as minimally invasive surgery (MIS) techniques [3] and the development of new, innovative surgical tools [4].

The overall definition of MIS includes surgical procedures that reduce the morbidity of conventional surgical trauma [5]. These techniques have been made possible primarily by the development and adoption of endoscopic systems and the continued miniaturization of imaging systems [5]. Insufflation devices can be used for the controlled inflation of body cavities and the creation of surgical workspaces [5]. In the last decade, the development of robotic-assisted surgery has provided another technological advancement for MIS, which is currently gaining importance [6]. The main advantages of MIS reported in the literature include reduced postoperative pain due to the avoidance of extensive surgical trauma [5]. This may also reduce the number of immobility related morbidities such as postoperative atelectasis or venous thrombosis [7]. In addition, MIS can help to improve the visibility of inaccessible areas, reduce the risk of inflammation, and improve recovery time and cosmesis [5]. Consequently, they can significantly reduce the mean LOS of patients [8][9][10].

One of the major disadvantages of MIS is the extended surgical "learning curve" [11]. with complications occurring early during this period [11]. Watson et al. identified the first 20 procedures as the interval with the highest risk of complications [12]. This finding has led to the widespread use of educational courses, simulators, web-based videos, and mentoring programs in surgical education and training [5]. In addition, there are procedure-specific risks such as insufflation complications, port site metastasis after laparoscopic ablative surgery, and hernia formation and bleeding [5]. Dissections through robotic-assisted minimally invasive procedures generally take longer than traditional open surgical approaches [6], which may be associated with lower operative turnover rates and corresponding economic disadvantages [5]. However, this disadvantage is usually offset by lower costs associated with a shorter LOS [5]. Today, there is a great demand for MIS procedures, and there are some potential opportunities to develop them further.

2. The Basics of Augmented Reality (AR) and Its Impact on Healthcare

The development of new technologies has come to the forefront, especially during the Corona pandemic [13]. Virtual reality (VR) and augmented reality (AR), also referred to as mixed reality (MR) [14], are among the three-dimensional (3D) technologies that have been used in consumer marketing for many decades and are currently gaining momentum in healthcare [15].

AR is a technology that overlays computer-generated images or videos onto real-world objects and environments [16]. The use of AR has the potential to revolutionize the way surgery is delivered and received [17]. AR has been shown to improve patient outcomes [18], increase the efficiency and accuracy of surgical procedures [19], and enhance medical education and training [20]. AR technologies such as AR glasses [21], AR head-mounted displays [22], and AR smartphones [23] are being developed and deployed in healthcare settings, with some early applications showing promising results [23]. However, AR in healthcare is still in its early stages of development, and there are several technical and regulatory challenges that must be addressed before it can be widely adopted [24].

3. How AR Technology Can Help Improve MIS Procedures

AR technology is gaining increasing interest in the development of minimally invasive surgery today [19]. This is reflected in the number of research articles published in recent years from a variety of medical disciplines. Although many studies have been published on this topic, some of them differ fundamentally in their research questions, data collection methods, and design, making it impossible to compare them in meta-analyses. In addition, most studies to date have been experimental and few have provided significant clinical benefits to patient care.

Most of the developments have been made in spine surgery/orthopedic surgery [25][26][27][28][29][30] and for endoscopic/laparoscopic procedures [26][31][32][33], which have not yet fully exploited the potential of this new technology. AR could help identify and visualize critical anatomical structures such as blood vessels and nerves to reduce the risk of injury or to guide the proper placement of surgical instruments [25][32].

To answer the question of how AR technology can help improve MIS procedures, researchers have identified three main areas of application. Most research today is focused on intraoperative AR-guided navigation. AR technology is also being used to improve education and surgical training and to develop and improve new user-environment interfaces.

While the studies discussed here indicate some potential of AR technology in the context of improving MIS navigation solutions [25][26][27][28][29][30][31][32][33][34][35][36][37][38][39][40], current AR-guided navigation systems have not shown improved precision compared to conventional navigation methods, albeit shown improvements in ergonomics and visualization have been reported [36]. However, what has been clinically demonstrated to date is evidence of shorter operative times and less blood loss, suggesting a gentler surgical approach [26][30]. Most of the AR-guided navigation studies presented here are experimental development approaches, some of which have shown promising results [27][29][31][32][33][38]. However, clinical trials with adequately sized numbers of patients or even systematic reviews demonstrating added value for patient care are still rare [25][26][35][36].

Although AR is predicted to revolutionize surgery, there are several challenges that need to be addressed to ensure widespread adoption [41][42][43][44]. A major issue, especially in soft tissue navigation, is the accuracy and reliability of the AR system, particularly in registering patient data and matching virtual and real views [41][42]. These are prone to errors, especially during intraoperative repositioning. It is moreover important for future research to identify factors for evaluating AR accuracy. For this purpose, Root Mean Square Distance (RMSD) or Root Mean Square Error (RMSE) has been proposed by some authors [32][42][44]. In addition, real-time processing, and visualization of a large amount of data for AR navigation is problematic because it is computationally intense and requires advanced hardware and software infrastructure [25][26][27][28][29][30][32][33][35][36][37][45][46]. Nevertheless, some promising developments in robotics, visualization, positioning, haptics, artificial intelligence, and computer vision have been presented that may help to further advance AR technology for clinical use [41][42][43][44].

Several studies have addressed the benefits of AR technology and its ability to enhance surgical education and training by providing students and professionals with an immersive, interactive, and engaging learning experience [20][47][48][49][50]. However, awareness of this technology among clinically active surgeons remains low [47]. Without requiring expensive equipment or putting patients at risk, trainees can practice and refine surgical procedures using virtual models of patient anatomy [45]. They receive real-time feedback on their performance, allowing them to refine their technique and improve patient outcomes in vivo. In addition, AR can be used to train surgeons in new or rare surgical procedures that are difficult to perform in the real world [48]. The benefits of virtual surgical training could, therefore, indeed impact MIS approaches. However, this influence has yet to be demonstrated via standardized studies with a large number of participants.

The interface between users and different surgical environments can be improved by using AR technology to provide relevant and contextual information in real-time [19][21][22][23][50][51]. Surgeons can visualize patient data and imaging scans in 3D, allowing for more accurate and personalized surgical planning [23]. It can enable remote collaboration and consultation between surgeons, facilitating knowledge sharing and improving patient outcomes [50]. However, to date, most studies on the topic of user interface improvement have been experimental or proof-of-concept approaches. So far, there is no evidence of added value for patient care.

References

1. Golder, H.J.; Papalois, V. Enhanced Recovery after Surgery: History, Key Advancements and Developments in Transplant Surgery. J. Clin. Med. 2021, 10, 1634.
2. Baek, H.; Cho, M.; Kim, S.; Hwang, H.; Song, M.; Yoo, S. Analysis of length of hospital stay using electronic health records: A statistical and data mining approach. PLoS ONE 2018, 13, e0195901.
3. Liu, C.; Pan, L.K. Advances in minimally invasive surgery and clinical measurement. Comput. Assist. Surg. 2019, 24, 1–4.
4. Hirst, A.; Philippou, Y.; Blazeby, J.; Campbell, B.; Campbell, M.; Feinberg, J.; Rovers, M.; Blencowe, N.; Pennell, C.; Quinn, T.; et al. No Surgical Innovation Without Evaluation: Evolution and Further Development of the IDEAL Framework and Recommendations. Ann. Surg. 2019, 269, 211–220.
5. Jaffray, B. Minimally invasive surgery. Arch. Dis. Child. 2005, 90, 537–542.
6. Prete, F.P.; Pezzolla, A.; Prete, F.; Testini, M.; Marzaioli, R.; Patriti, A.; Jimenez-Rodriguez, R.M.; Gurrado, A.; Strippoli, G.F.M. Robotic Versus Laparoscopic Minimally Invasive Surgery for Rectal Cancer: A Systematic Review and Meta-analysis of Randomized Controlled Trials. Ann. Surg. 2018, 267, 1034–1046.
7. Karayiannakis, A.J.; Makri, G.G.; Mantzioka, A.; Karousos, D.; Karatzas, G. Postoperative pulmonary function after laparoscopic and open cholecystectomy. Br. J. Anaesth. 1996, 77, 448–452.
8. Zureikat, A.H.; Beane, J.D.; Zenati, M.S.; Al Abbas, A.I.; Boone, B.A.; Moser, A.J.; Bartlett, D.L.; Hogg, M.E.; Zeh, H.J., 3rd. 500 Minimally Invasive Robotic Pancreatoduodenectomies: One Decade of Optimizing Performance. Ann. Surg. 2021, 273, 966–972.
9. de Rooij, T.; Lu, M.Z.; Steen, M.W.; Gerhards, M.F.; Dijkgraaf, M.G.; Busch, O.R.; Lips, D.J.; Festen, S.; Besselink, M.G. Minimally Invasive Versus Open Pancreatoduodenectomy: Systematic Review and Meta-analysis of Comparative Cohort and Registry Studies. Ann. Surg. 2016, 264, 257–267.
10. Chadi, S.A.; Guidolin, K.; Caycedo-Marulanda, A.; Sharkawy, A.; Spinelli, A.; Quereshy, F.A.; Okrainec, A. Current Evidence for Minimally Invasive Surgery During the COVID-19 Pandemic and Risk Mitigation Strategies: A Narrative Review. Ann. Surg. 2020, 272, e118–e124.
11. Chen, M.K.; Schropp, K.P.; Lobe, T.E. Complications of minimal-access surgery in children. J. Pediatr. Surg. 1996, 31, 1161–1165.
12. Watson, D.I.; Baigrie, R.J.; Jamieson, G.G. A learning curve for laparoscopic fundoplication. Definable, avoidable, or a waste of time? Ann. Surg. 1996, 224, 198–203.
13. Chandra, M.; Kumar, K.; Thakur, P.; Chattopadhyaya, S.; Alam, F.; Kumar, S. Digital technologies, healthcare and COVID-19: Insights from developing and emerging nations. Health Technol. 2022, 12, 547–568.
14. Milgram, P.; Kishino, F. A Taxonomy of Mixed Reality Visual Displays. IEICE Trans. Inf. Syst. 1994, E77-D, 1321–1329.
15. Wedel, M.; Bigné, E.; Zhang, J. Virtual and augmented reality: Advancing research in consumer marketing. Int. J. Res. Mark. 2020, 37, 443–465.
16. Chen, Y.; Wang, Q.; Chen, H.; Song, X.; Tang, H.; Tian, M. An overview of augmented reality technology. J. Phys. Conf. Ser. 2019, 1237, 022082.
17. Munzer, B.W.; Khan, M.M.; Shipman, B.; Mahajan, P. Augmented reality in emergency medicine: A scoping review. J. Med. Internet Res. 2019, 21, e12368.
18. Naziri, Q.; Mixa, P.J.; Murray, D.P.; Abraham, R.; Zikria, B.A.; Sastry, A.; Patel, P.D. Robotic-Assisted and Computer-Navigated Unicompartmental Knee Arthroplasties: A Systematic Review. Surg. Technol. Int. 2018, 32, 271–278.
19. Vavra, P.; Roman, J.; Zonca, P.; Ihnat, P.; Nemec, M.; Kumar, J.; Habib, N.; El-Gendi, A. Recent Development of Augmented Reality in Surgery: A Review. J. Healthc. Eng. 2017, 2017, 4574172.
20. Herron, J. Augmented reality in medical education and training. J. Electron. Resour. Med. Libr. 2016, 13, 51–55.
21. Basoglu, N.A.; Goken, M.; Dabic, M.; Ozdemir Gungor, D.; Daim, T.U. Exploring adoption of augmented reality smart glasses: Applications in the medical industry. Front. Eng. 2018, 5, 167–181.

22. Gallos, P.; Georgiadis, C.; Liaskos, J.; Mantas, J. Augmented reality glasses and head-mounted display devices in healthcare. In Data, Informatics and Technology: An Inspiration for Improved Healthcare; IOS Press: Amsterdam, The Netherlands, 2018; pp. 82–85.

23. Moro, C.; Štromberga, Z.; Raikos, A.; Stirling, A. The effectiveness of virtual and augmented reality in health sciences and medical anatomy. Anat. Sci. Educ. 2017, 10, 549–559.

24. Chen, L.; Day, T.W.; Tang, W.; John, N.W. Recent developments and future challenges in medical mixed reality. In Proceedings of the 2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Nantes, France, 9–13 October 2017; pp. 123–135.

25. Butler, A.J.; Colman, M.W.; Lynch, J.; Phillips, F.M. Augmented reality in minimally invasive spine surgery: Early efficiency and complications of percutaneous pedicle screw instrumentation. Spine J. 2023, 23, 27–33.

26. Guo, Q.; Li, X.; Tang, Y.; Huang, Y.; Luo, L. Augmented reality and three-dimensional plate library-assisted posterior minimally invasive surgery for scapula fracture. Int. Orthop. 2022, 46, 875–882.

27. Felix, B.; Kalatar, S.B.; Moatz, B.; Hofstetter, C.; Karsy, M.; Parr, R.; Gibby, W. Augmented Reality Spine Surgery Navigation: Increasing Pedicle Screw Insertion Accuracy for Both Open and Minimally Invasive Spine Surgeries. Spine 2022, 47, 865–872.

28. Yuk, F.J.; Maragkos, G.A.; Sato, K.; Steinberger, J. Current innovation in virtual and augmented reality in spine surgery. Ann. Transl. Med. 2021, 9, 94.

29. Chen, F.; Cui, X.; Han, B.; Liu, J.; Zhang, X.; Liao, H. Augmented reality navigation for minimally invasive knee surgery using enhanced arthroscopy. Comput. Methods Programs Biomed. 2021, 201, 105952.

30. Hu, M.H.; Chiang, C.C.; Wang, M.L.; Wu, N.Y.; Lee, P.Y. Clinical feasibility of the augmented reality computer-assisted spine surgery system for percutaneous vertebroplasty. Eur. Spine J. 2020, 29, 1590–1596.

31. Zadeh, S.M.; François, T.; Comptour, A.; Canis, M.; Bourdel, N.; Bartoli, A. SurgAI3.8K: A labelled dataset of gynaecologic organs in laparoscopy, with application to automatic augmented reality surgical guidance. J. Minim. Invasive Gynecol. 2023.

32. Zhu, T.; Jiang, S.; Yang, Z.; Zhou, Z.; Li, Y.; Ma, S.; Zhuo, J. A neuroendoscopic navigation system based on dual-mode augmented reality for minimally invasive surgical treatment of hypertensive intracerebral hemorrhage. Comput. Biol. Med. 2022, 140, 105091.

33. Lecointre, L.; Verde, J.; Goffin, L.; Venkatasamy, A.; Seeliger, B.; Lodi, M.; Swanström, L.L.; Akladios, C.; Gallix, B. Robotically assisted augmented reality system for identification of targeted lymph nodes in laparoscopic gynecological surgery: A first step toward the identification of sentinel node: Augmented reality in gynecological surgery. Surg. Endosc. 2022, 36, 9224–9233.

34. Xu, L.; Zhang, H.; Wang, J.; Li, A.; Song, S.; Ren, H.; Qi, L.; Gu, J.J.; Meng, M.Q.H. Information loss challenges in surgical navigation systems: From information fusion to AI-based approaches. Inf. Fusion 2023, 92, 13–36.

35. Benmahdjoub, M.; van Walsum, T.; van Twisk, P.; Wolvius, E.B. Augmented reality in craniomaxillofacial surgery: Added value and proposed recommendations through a systematic review of the literature. Int. J. Oral Maxillofac. Surg. 2021, 50, 969–978.

36. Hussain, R.; Lalande, A.; Guigou, C.; Bozorg-Grayeli, A. Contribution of Augmented Reality to Minimally Invasive Computer-Assisted Cranial Base Surgery. IEEE J. Biomed. Health Inform. 2020, 24, 2093–2106.

37. Hussain, I.; Cosar, M.; Kirnaz, S.; Schmidt, F.A.; Wipplinger, C.; Wong, T.; Härtl, R. Evolving Navigation, Robotics, and Augmented Reality in Minimally Invasive Spine Surgery. Glob. Spine J. 2020, 10, 22s–33s.

38. Gribaudo, M.; Piazzolla, P.; Porpiglia, F.; Vezzetti, E.; Violante, M.G. 3D augmentation of the surgical video stream: Toward a modular approach. Comput. Methods Programs Biomed. 2020, 191, 105505.

39. Chauvet, P.; Bourdel, N.; Calvet, L.; Magnin, B.; Teluob, G.; Canis, M.; Bartoli, A. Augmented Reality with Diffusion Tensor Imaging and Tractography during Laparoscopic Myomectomies. J. Minim. Invasive Gynecol. 2020, 27, 973–976.

40. Brebant, V.; Heine, N.; Lamby, P.; Heidekrueger, P.I.; Forte, A.J.; Prantl, L.; Aung, T. Augmented reality of indocyanine green fluorescence in simplified lymphovenous anastomosis in lymphatic surgery. Clin. Hemorheol. Microcirc. 2019, 73, 125–133.

41. Li, R.; Pan, J.; Yang, Y.; Wei, N.; Yan, B.; Liu, H.; Yang, Y.; Qin, H. Accurate and robust feature description and dense point-wise matching based on feature fusion for endoscopic images. Comput. Med. Imaging Graph. 2021, 94, 102007.

42. Jia, T.; Taylor, Z.A.; Chen, X. Long term and robust 6DoF motion tracking for highly dynamic stereo endoscopy videos. Comput. Med. Imaging Graph. 2021, 94, 101995.

43. Wang, R.; Zhang, M.; Meng, X.; Geng, Z.; Wang, F.Y. 3-D Tracking for Augmented Reality Using Combined Region and Dense Cues in Endoscopic Surgery. IEEE J. Biomed. Health Inform. 2018, 22, 1540–1551.
44. Chen, L.; Tang, W.; John, N.W.; Wan, T.R.; Zhang, J.J. SLAM-based dense surface reconstruction in monocular Minimally Invasive Surgery and its application to Augmented Reality. Comput. Methods Programs Biomed. 2018, 158, 135–146.
45. Wild, C.; Lang, F.; Gerhäuser, A.S.; Schmidt, M.W.; Kowalewski, K.F.; Petersen, J.; Kenngott, H.G.; Müller-Stich, B.P.; Nickel, F. Telestration with augmented reality for visual presentation of intraoperative target structures in minimally invasive surgery: A randomized controlled study. Surg. Endosc. 2022, 36, 7453–7461.
46. Thabit, A.; Benmahdjoub, M.; van Veelen, M.C.; Niessen, W.J.; Wolvius, E.B.; van Walsum, T. Augmented reality navigation for minimally invasive craniosynostosis surgery: A phantom study. Int. J. Comput. Assist. Radiol. Surg. 2022, 17, 1453–1460.
47. Balla, A.; Sartori, A.; Botteri, E.; Podda, M.; Ortenzi, M.; Silecchia, G.; Guerrieri, M.; Agresta, F. Augmented reality (AR) in minimally invasive surgery (MIS) training: Where are we now in Italy? The Italian Society of Endoscopic Surgery (SICE) ARMIS survey. Updates Surg. 2023, 75, 85–93.
48. Gholizadeh, M.; Bakhshali, M.A.; Mazlooman, S.R.; Aliakbarian, M.; Gholizadeh, F.; Eslami, S.; Modrzejewski, A. Minimally invasive and invasive liver surgery based on augmented reality training: A review of the literature. J. Robot. Surg. 2022.
49. Godzik, J.; Farber, S.H.; Urakov, T.; Steinberger, J.; Knipscher, L.J.; Ehredt, R.B.; Tumialán, L.M.; Uribe, J.S. “Disruptive Technology” in Spine Surgery and Education: Virtual and Augmented Reality. Oper. Neurosurg. 2021, 21, S85–S93.
50. Stewart, C.L.; Fong, A.; Payyavula, G.; DiMaio, S.; Lafaro, K.; Tallmon, K.; Wren, S.; Sorger, J.; Fong, Y. Study on augmented reality for robotic surgery bedside assistants. J. Robot. Surg. 2022, 16, 1019–1026.
51. Forte, M.P.; Gourishetti, R.; Javot, B.; Engler, T.; Gomez, E.D.; Kuchenbecker, K.J. Design of interactive augmented reality functions for robotic surgery and evaluation in dry-lab lymphadenectomy. Int. J. Med. Robot. 2022, 18, e2351.