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Review Article
Application of mixed reality technology in surgery

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Abstract: Mixed reality, a new generation of technology, has attracted much attention in recent years. Technologic advances have enabled technology to gain increased recognition in medical application, especially in surgery. The emergence of technology has changed the traditional surgical training mode, providing a highly efficient and cost-effective training method for trainees. Moreover, technology has the potential to reduce the risk of surgery and time spent in the operating room. Technology will undoubtedly play a significant role in the future, assist surgeons in safely and effectively completing more risky operations. The aim of this study was to explore advantages and disadvantages of the utilization of mixed reality technology in the surgical field.

Keywords: Mixed reality, virtual reality, augmented reality, application, surgery

Background

Surgeons are regularly on the lookout for new technologies to improve work efficiency. Virtual reality (VR) and augmented reality (AR) have been increasingly applied in the field of medicine, especially in surgery [1-3]. In the two kinds of reality, VR creates an artificial 3-dimensional simulated environment, allowing users to completely immerse themselves in a simulated world [4, 5]. Due to a lack of realism, VR cannot be used in real procedures. Clinicians find it difficult to immerse themselves in the situation [6, 7]. AR, which generally refers to the integration of additional information or graphical elements with the user's environment in real time [8], is different from VR. AR performs the task's interaction focus in the real world, rather than in a totally artificial environment [9]. Most AR solutions rely on complicated external navigation systems and cumbersome devices, however, limiting its use in routine surgical procedures [10, 11].

The solution might lie in an emerging technology known as mixed reality (MR) [12], providing users with an environment to perceive both the physical environment around them and digital elements (virtual objects) presented through displays [13]. This technology gives users the illusion that digital objects and physical objects coexist in the same space. Researchers and surgeons have explored the effects of MR technology on the surgical field, such as surgical training, preoperative planning, and intraoperative guidance. Compared with traditional methods, MR technology has been considered as a cost-effective and efficient tool in the above-mentioned fields. The current study will discuss advantages and disadvantages of the utilization of MR technology in the surgical field. Moreover, future trends of this technology in the field of surgery are discussed.

Main text

Surgical training

For decades, the only way for junior doctors to receive surgical training and acquire surgical skills was under the supervision of a senior surgeon in the operating room [14]. The traditional apprenticeship model of surgical training has been considered to be expensive and time-consuming [15]. With an increasing number of trainees, the opportunity to acquire the necessary surgical skills has become limited because of rising costs, reduced working hours, and ethical issues [16]. About 10 percent of patients have been reported to have suffered unnecessary surgical complications caused by human error [17-19]. Consequently, it is essential for surgeons to explore highly effective teaching and training approaches, aiming to increase success rates and decrease surgical risks.

Numerous surgical training methods are commercially available, including video games, animal models, cadavers, and simulation-based models [20]. Several studies have argued that video games can be used to enhance surgical competence in surgical trainees, as it improves spatial relationships and visual attentional capacity and enables visual multitasking [21-23]. However, studies have shown that, although video gaming improves basic surgical skills, it is unable to influence more complex surgical skills [23, 24]. Animal models play an essential role in surgical training, education, and research [25]. However, living animal models have many limitations, such as ethical responsibilities, financial obligation, and absence of faculty [26]. Training surgical skills on a cadaver, although providing the greatest anatomical realism, has become more expensive and more tightly regulated due to difficulties in obtaining cadavers and ethical issues [27-29].

Recently, given concerns about financial constraints, quality control, and patient safety, surgical training has quickly converted to the use simulation to train residents. This allows them to acquire and update surgical skills [30, 31]. Simulation harbors the potential to enhance experiential learning, ensure patient safety, and reproduce scenarios that are rarely seen [15]. At present, MR surgical simulators are an integral part of physician training, as they provide risk-free training [13]. Using MR surgical simulators, novice surgeons can view and experience complex surgeries without stepping into the operating room. Furthermore, through real-time visual augmentation (3D visualization) in the MR simulator, participant confidence in performing unfamiliar techniques is improved, especially for unfamiliar techniques [32]. Hooten et al. introduced a novel mixed physical and virtual simulator, providing a real-life experience to mimic the ventriculostomy procedure. Results showed that most residents thought it was helpful to practice ventriculostomies in the simulator. Mixed reality simulators can provide real-life experiences and may become an essential tool in training the next generation of neurosurgeons [33].

Consequently, MR technology can be used to complement existing simulations, creating a realistic and reproducible surgical training platform for trainees [34]. Surgical residents, with MR simulations, can receive accredited training. Existing surgeons will be able to update and refresh their surgical knowledge and skills.

Preoperative planning

In an age where operative time is valuable and ethical considerations play an essential role, surgeons are less likely to develop surgical skills during surgery [35, 36]. Therefore, preoperative planning is an indispensable part of any successful surgical procedure [37]. Preoperative planning is a complex task, requiring high levels of perception, cognitive, and sensorimotor skills to reduce surgical complications [38]. For complex surgeries, detailed preoperative planning can predict and reduce risks that may occur in the operation, thereby increasing safety. Traditional surgical planning depends on preoperative radiographic images, which are essential in understanding the anatomy of the patient, identifying appropriate treatment options, and preparing a surgical plan. However, the variability and magnification of image quality may affect the accuracy of preoperative estimations [39]. With the rapid development of computer imaging technology, digital imaging systems have made great progress in the quality of images, as well as cost and time issues. Thus, it has gradually replaced conventional radiography [40]. However, for complex surgeries, standard radiographs do not meet the surgeon's full understanding of complex anatomical structures. With the development of three dimensional reconstruction and rapid prototyping technology, surgeons can perform preoperative planning and procedure rehearsals on a 3D model of precise sizes and shapes before surgery [41]. What should be carefully examined is the time required and the price to manufacture rapid prototyping models [37]. Although the 3D physical model is more natural and tangible, it has no interactive capability [42].

With the application of MR technology in the field of surgery, surgeons can produce a virtual

3D anatomical structure model of the patient and perform surgical exercises on virtual models. This provides a more intuitive and profound understanding of the patient's anatomy before surgery. Surgeons can use this technique to perform preoperative simulations, determining the optimal surgical procedure. Moreover, preoperative surgical planning using MR technology can provide more realistic predictions for surgical results [3]. Fushima and Kobayashi introduced a mixed reality-based system that synchronized the motion of the dental cast model in the real world and a 3D patient model in the virtual world [43]. In the preoperative plan, the operator can simulate a jaw osteotomy on the PC monitor, then determine the position of the final jaws after several attempts. Based on the measurement data of actual lower dental cast, the measurement error of the whole simulation system is less than 0.32 mm, indicating that its accuracy is sufficient to meet clinical needs.

Good communication between doctors and patients is also an important component of medicine practice. In the course of medical service, the most important factor of medical disputes is the lack of communication between patients with doctors. One reason for the lack of communication is the asymmetry of information between doctors and patients. Especially for complex surgeries, it is difficult for patients and their families to have an intuitive understanding of the procedures through traditional preoperative talking. MR devices are enabling technologies which can promote effective communication between those with information and knowledge (clinicians) and those seeking understanding and insight (patients) [44]. In preoperative conversation, using MR techniques to simulate the operation, patients and their families will have a more intuitive understanding of the operation process.

Preoperative planning and simulations have been an imperative part of surgery in many health centers [45]. MR simulations may become the most important and effective preoperative planning method in the future.

Intraoperative guidance

During an operation, the surgeon is required to have a precise understanding of the position and direction of the surgical instrument. The traditional surgical navigation system is used to track tools and patients. It can help surgeons with their mental alignment and localization [11]. Although the accuracy of modern navigation is high [46, 47], they cannot reduce operation room times and require complex preoperative calibration and occupancy of valuable space [48, 49]. MR technology can present an advanced form of image guidance, enabling surgeons to see anatomical structures and surgical instruments from the patient's surface. The visualization of MR allows doctors to interpret diagnostic, planning, and instructional information at the site [50].

For instance, orthopedic surgery is technically challenging, due to the complexity of the anatomical structure and the complicated procedure. It takes a lot of effort and time to place screws without a little deviation in a percutaneous pelvis fixation procedure. These will inevitably lead to relatively long operation times and high radiation exposure for patients and surgeons. Lee et al. introduced a MR support system that incorporated multi-modal data fusion and model-based surgical tool tracking, aiming to provide orthopedic surgeons intuitive understanding of surgical sites and to help them quickly and accurately insert screws [11]. They combined a MR visualization with an advanced tracking technique to demonstrate the patient's anatomy, surgical plans, and objects within the surgical site in real time. Studies have shown that the visualized system reduces radiation doses by 63.9% and reduces surgical times by 59.1% [51]. Moreover, MR technology was applied to a complex visceral surgery by Sauer et al. [52]. Using the MR head-mount display, the surgeon could see a 3D-model of the patient's relevant liver structures above the surgical site, improving the surgeon's action and perception.

In addition, MR technology had also been applied in orthognathic surgery [43], neurosurgical procedures [53], and urinary surgery [8], shortening operation times, reducing exposure to radiation, and improving efficiency [11].

Advantages and disadvantages

The emergence of MR technology brings many new possibilities to the surgical field. MR, which merges numerous virtual reality and augmented realty features, has great potential to ameliorate inconveniences encountered during surgery. It can shorten the learning curve, reduce risks for patients, and achieve better surgical outcomes [50]. The main advantages of MR in the field of surgery are as follows:

- MR simulator has the ability to reduce learning curves and ease trainee transition to actual patients [13].

- MR technology can actually improve the efficiency of the surgeon.

- MR technology is able to lower risks for patients and achieve better surgical outcomes [50].

Although MR technology introduces many new possibilities for surgery, there are certain limitations. The latency of the system is one of the concerns. Too much delay can reduce the accuracy of the operation and reduce the comfort of the surgeon [54]. The currently used head-mounted displays of MR usually weigh hundreds of grams. Thus, wearing it comfortably for a long time is a problem. However, with the development of network technology and multimedia, these problems will be gradually solved.

Prospects for MR technology

Besides the abovementioned fields, MR technology has great potential for use in telemedicine.

At present, due to a lack of healthcare providers, many remote rural areas still lack health care services. An economically efficient solution to the shortage of healthcare providers in rural areas is telemedicine, which uses information technology to provide health care at different distances [55]. Telemedicine, which uses the telecommunication technology to provide long-distance medical services, has become an innovative tool in the field of surgery [56]. It can increase patient satisfaction, while reducing mismanagement and unnecessary patient transfer, waiting times, and costs associated with patients and providers [55, 57, 58].

In 2001, Marescaux, in New York, performed the first case of telesurgery on a French patient [59]. The limitation of the traditional remote robot-assisted telesurgery is the cost of the robotic machine, approximately $1 million. Moreover, another important problem with remote surgery is the lack of face-to-face contact between the patient and surgeon [59]. MR technology, which is more cost-effective, is expected to break the limitation of time and space, bringing remote experts into the local operating room. On January 10, 2018, Ye et al. successfully carried out the world's first remote consultation operation in the world using MR technology. In terms of effectiveness, precision, and safety, MR technology, in the opinion of Professor Ye, has incomparable advantages. These advantages will be highlighted especially in emergencies and critically ill patients.

Latency has been considered to be one of the major defects in current telemedicine [60, 61]. The latency of more than 105 ms may affect surgical performance and the user experience [62]. The 5G network will be fully deployed in 2020, with many advantages, such as higher mobility support, massive connectivity, and reduced latency [63, 64]. Emergence of the 5G network will be a good solution for latency of the MR technology in telemedicine, bringing the real-time transmission of data. In addition, considering the cost effectiveness of MR technology, it has broad prospects in the field of telemedicine.

Conclusion

MR has been progressively used in the surgical field. Emergence of MR technology has changed the traditional surgical training mode, providing a highly efficient and cost-effective training method for trainees. Moreover, MR technology has the potential to reduce risks of surgery and time spent in the operating room, through its use in preoperative planning and intraoperative guidance. MR technology will play a significant increasing role in the future, assisting surgeons in safely and effectively completing more risky operations. Moreover, with the advent of 5G network, application of MR technology will provide higher quality prompt medical services for people in remote areas.

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Disclosure of conflict of interest

None.

Abbreviations

VR, Virtual reality; AR, Augmented reality; MR, Mixed reality.

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References

[1] Pulijala Y, Ma M, Pears M, Peebles D and Ayoub A. An innovative virtual reality training tool for orthognathic surgery. Int J Oral Maxillofac Surg 2018; 47: 1199-1205.
[2] Zahiri M, Nelson CA, Oleynikov D and Siu KC. Evaluation of augmented reality feedback in surgical training environment. Surg Innov 2018; 25: 81-87.
[3] Kim Y, Kim H and Kim YO. Virtual reality and augmented reality in plastic surgery: a review. Arch Plast Surg 2017; 44: 179-187.
[4] Li A, Montano Z, Chen VJ and Gold JI. Virtual reality and pain management: current trends and future directions. Pain Manag 2011; 1: 147-157.
[5] Arane K, Behboudi A and Goldman RD. Virtual reality for pain and anxiety management in children. Can Fam Physician 2017; 63: 932-934.
[6] De Ribaupierre S and Eagleson R. Editorial: challenges for the usability of AR and VR for clinical neurosurgical procedures. Healthc Technol Lett 2017; 4: 151.
[7] Fertleman C, Aubugeau-Williams P, Sher C, Lim AN, Lumley S, Delacroix S and Pan X. A discussion of virtual reality as a new tool for training healthcare professionals. Front Public Health 2018; 6: 44.
[8] Hamacher A, Kim SJ, Cho ST, Pardeshi S, Lee SH, Eun SJ and Whangbo TK. Application of virtual, augmented, and mixed reality to urology. Int Neurourol J 2016; 20: 172-181.
[9] Barsom EZ, Graafland M and Schijven MP. Systematic review on the effectiveness of augmented reality applications in medical training. Surg Endosc 2016; 30: 4174-4183.
[10] Khor WS, Baker B, Amin K, Chan A, Patel K and Wong J. Augmented and virtual reality in surgery-the digital surgical environment: applications, limitations and legal pitfalls. Ann Transl Med 2016; 4: 454.
[11] Lee SC, Fuerst B, Tateno K, Johnson A, Fotouhi J, Osgood G, Tombari F and Navab N. Multi-modal imaging, model-based tracking, and mixed reality visualisation for orthopaedic surgery. Healthc Technol Lett 2017; 4: 168-173.
[12] Tepper OM, Rudy HL, Lefkowitz A, Weimer KA, Marks SM, Stern CS and Garfein ES. Mixed reality with holoLens: where virtual reality meets augmented reality in the operating room. Plast Reconstr Surg 2017; 140: 1066-1070.
[13] Halic T, Kockara S, Bayrak C and Rowe R. Mixed reality simulation of rasping procedure in artificial cervical disc replacement (ACDR) surgery. BMC Bioinformatics 2010; 11 Suppl 6: S11.
[14] Aim F, Lonjon G, Hannouche D and Nizard R. Effectiveness of virtual reality training in orthopaedic surgery. Arthroscopy 2016; 32: 224-232.
[15] Choy I and Okrainec A. Simulation in surgery: perfecting the practice. Surg Clin North Am 2010; 90: 457-473.
[16] Li L, Yu F, Shi D, Shi J, Tian Z, Yang J, Wang X and Jiang Q. Application of virtual reality technology in clinical medicine. Am J Transl Res 2017; 9: 3867-3880.
[17] Baker GR, Norton PG, Flintoft V, Blais R, Brown A, Cox J, Etchells E, Ghali WA, Hebert P, Majumdar SR, O'Beirne M, Palacios-Derflingher L, Reid RJ, Sheps S and Tamblyn R. The canadian adverse events study: the incidence of adverse events among hospital patients in Canada. CMAJ 2004; 170: 1678-1686.
[18] Pucher PH, Aggarwal R, Almond MH and Darzi A. Surgical care checklists to optimize patient care following postoperative complications. Am J Surg 2015; 210: 517-525.
[19] Bonrath EM, Gordon LE and Grantcharov TP. Characterising 'near miss' events in complex laparoscopic surgery through video analysis. BMJ Qual Saf 2015; 24: 516-521.
[20] Forgione A and Guraya SY. The cutting-edge training modalities and educational platforms for accredited surgical training: a systematic review. J Res Med Sci 2017; 22: 51.
[21] Van Hove C, Perry KA, Spight DH, Wheeler-Mcinvaille K, Diggs BS, Sheppard BC, Jobe BA and O'Rourke RW. Predictors of technical skill ac-

quisition among resident trainees in a laparoscopic skills education program. World J Surg 2008; 32: 1917-1921.
[22] Green CS and Bavelier D. Action video game modifies visual selective attention. Nature 2003; 423: 534-537.
[23] Goris J, Jalink MB and Ten Cate Hoedemaker HO. Training basic laparoscopic skills using a custom-made video game. Perspect Med Educ 2014; 3: 314-318.
[24] Rosenberg BH, Landsittel D and Averch TD. Can video games be used to predict or improve laparoscopic skills? J Endourol 2005; 19: 372-376.
[25] DeMasi SC, Katsuta E and Takabe K. Live animals for preclinical medical student surgical training. Edorium J Surg 2016; 3: 24-31.
[26] Daly SC, Wilson NA, Rinewalt DE, Bines SD, Luu MB and Myers JA. A subjective assessment of medical student perceptions on animal models in medical education. J Surg Educ 2014; 71: 61-64.
[27] Zuckerman JD, Wise SK, Rogers GA, Senior BA, Schlosser RJ and DelGaudio JM. The utility of cadaver dissection in endoscopic sinus surgery training courses. Am J Rhinol Allergy 2009; 23: 218-224.
[28] Rocha e Silva R, Lourencao A Jr, Goncharov M and Jatene FB. Low cost simulator for heart surgery training. Braz J Cardiovasc Surg 2016; 31: 449-453.
[29] Jacobson S, Epstein SK, Albright S, Ochieng J, Griffiths J, Coppersmith V and Polak JF. Creation of virtual patients from CT images of cadavers to enhance integration of clinical and basic science student learning in anatomy. Med Teach 2009; 31: 749-751.
[30] Bova FJ, Rajon DA, Friedman WA, Murad GJ, Hoh DJ, Jacob RP, Lampotang S, Lizdas DE, Lombard G and Lister JR. Mixed-reality simulation for neurosurgical procedures. Neurosurgery 2013; 73 Suppl 1: 138-145.
[31] Stefan P, Pfandler M, Wucherer P, Habert S, Furmetz J, Weidert S, Euler E, Eck U, Lazarovici M, Weigl M and Navab N. [Team training and assessment in mixed reality-based simulated operating room : current state of research in the field of simulation in spine surgery exemplified by the ATMEOS project]. Unfallchirurg 2018; 121: 271-277.
[32] Sappenfield JW, Smith WB, Cooper LA, Lizdas D, Gonsalves DB, Gravenstein N, Lampotang S and Robinson AR 3rd. Visualization improves supraclavicular access to the subclavian vein in a mixed reality simulator. Anesth Analg 2018;127: 83-89.
[33] Hooten KG, Lister JR, Lombard G, Lizdas DE, Lampotang S, Rajon DA, Bova F and Murad GJ. Mixed reality ventriculostomy simulation: experience in neurosurgical residency. Neurosurgery 2014; 4: 576-581.
[34] Hochman JB, Sepehri N, Rampersad V, Kraut J, Khazraee M, Pisa J and Unger B. Mixed reality temporal bone surgical dissector: mechanical design. J Otolaryngol Head Neck Surg 2014; 43: 23.
[35] Reznick RK and MacRae H. Teaching surgical skills-changes in the wind. N Engl J Med 2006; 355: 2664-2669.
[36] Niederee MJ, Knudtson JL, Byrnes MC, Helmer SD and Smith RS. A survey of residents and faculty regarding work hour limitations in surgical training programs. Arch Surg 2003; 138: 663-669.
[37] Atesok K, Galos D, Jazrawi LM and Egol KA. Preoperative planning in orthopaedic surgery. Current practice and evolving applications. Bull Hosp Jt Dis 2015; 73: 257-268.
[38] Abhari K, Baxter JS, Chen EC, Khan AR, Peters TM, de Ribaupierre S and Eagleson R. Training for planning tumour resection: augmented reality and human factors. IEEE Trans Biomed Eng 2015; 62: 1466-1477.
[39] Whiddon DR, Bono JV, Lang JE, Smith EL and Salyapongse AK. Accuracy of digital templating in total hip arthroplasty. Am J Orthop (Belle Mead NJ) 2011; 40: 395-398.
[40] Steinmetz MP, Mroz TE, Krishnaney A and Modic M. Conventional versus digital radiographs for intraoperative cervical spine-level localization: a prospective time and cost analysis. Spine J 2009; 9: 967-971.
[41] Hurson C, Tansey A, O'Donnchadha B, Nicholson P, Rice J and McElwain J. Rapid prototyping in the assessment, classification and preoperative planning of acetabular fractures. Injury 2007; 38: 1158-1162.
[42] Seitel M, Maier-Hein L, Rietdorf U, Nikoloff S, Seitel A, Franz A, Kenngott H, Karck M, De Simone R, Wolf I and Meinzer HP. Towards a mixed reality environment for preoperative planning of cardiac surgery. Stud Health Technol Inform 2009; 142: 307-309.
[43] Fushima K and Kobayashi M. Mixed-reality simulation for orthognathic surgery. Maxillofac Plast Reconstr Surg 2016; 38: 13.
[44] Kobayashi L, Zhang XC, Collins SA, Karim N and Merck DL. Exploratory application of augmented reality/mixed reality devices for acute care procedure training. West J Emerg Med 2018; 19: 158-164.
[45] Heuts S, Sardari Nia P and Maessen JG. Preoperative planning of thoracic surgery with use of three-dimensional reconstruction, rapid prototyping, simulation and virtual navigation. J Vis Surg 2016; 2: 77.
[46] Matthews F, Hoigne DJ, Weiser M, Wanner GA, Regazzoni P, Suhm N and Messmer P. Navi-

gating the fluoroscope's C-arm back into position: an accurate and practicable solution to cut radiation and optimize intraoperative workflow. J Orthop Trauma 2007; 21: 687-692.

[47] Liu L, Ecker T, Schumann S, Siebenrock K, Nolte L and Zheng G. Computer assisted planning and navigation of periacetabular osteotomy with range of motion optimization. Med Image Comput Comput Assist Interv 2014; 17: 643-650.

[48] Boszczyk BM, Bierschneider M, Panzer S, Panzer W, Harstall R, Schmid K and Jaksche H. Fluoroscopic radiation exposure of the kyphoplasty patient. Eur Spine J 2006; 15: 347-355.

[49] Synowitz M and Kiwit J. Surgeon's radiation exposure during percutaneous vertebroplasty. J Neurosurg Spine 2006; 4: 106-109.

[50] Linte CA, Davenport KP, Cleary K, Peters C, Vosburgh KG, Navab N, Edwards PE, Jannin P, Peters TM, Holmes DR 3rd and Robb RA. On mixed reality environments for minimally invasive therapy guidance: systems architecture, successes and challenges in their implementation from laboratory to clinic. Comput Med Imaging Graph 2013; 37: 83-97.

[51] Fischer M, Fuerst B, Lee SC, Fotouhi J, Habert S, Weidert S, Euler E, Osgood G and Navab N. Preclinical usability study of multiple augmented reality concepts for K-wire placement. Int J Comput Assist Radiol Surg 2016; 11: 1007-1014.

[52] Sauer IM, Queisner M, Tang P, Moosburner S, Hoepfner O, Horner R, Lohmann R and Pratschke J. Mixed reality in visceral surgery: development of a suitable workflow and evaluation of intraoperative use-cases. Ann Surg 2017; 266: 706-712.

[53] Kersten-Oertel M, Gerard I, Drouin S, Mok K, Sirhan D, Sinclair DS and Collins DL. Augmented reality in neurovascular surgery: feasibility and first uses in the operating room. Int J Comput Assist Radiol Surg 2015; 10: 1823-1836.

[54] Vavra P, Roman J, Zonca P, Ihnat P, Nemec M, Kumar J, Habib N and El-Gendi A. Recent development of augmented reality in surgery: a review. J Healthc Eng 2017; 2017: 4574172.

[55] Aarnio P, Rudenberg H, Ellonen M and Jaatinen P. User satisfaction with teleconsultations for surgery. J Telemed Telecare 2000; 6: 237-241.

[56] Whitten P and Mair F. Telesurgery versus telemedicine in surgery--an overview. Surg Technol Int 2004; 12: 68-72.

[57] Doze S, Simpson J, Hailey D and Jacobs P. Evaluation of a telepsychiatry pilot project. J Telemed Telecare 1999; 5: 38-46.

[58] Gardiner S and Hartzell TL. Telemedicine and plastic surgery: a review of its applications, limitations and legal pitfalls. J Plast Reconstr Aesthet Surg 2012; 65: e47-53.

[59] Marescaux J, Leroy J, Rubino F, Smith M, Vix M, Simone M and Mutter D. Transcontinental robot-assisted remote telesurgery: feasibility and potential applications. Ann Surg 2002; 235: 487-492.

[60] Wang S, Parsons M, Stone-McLean J, Rogers P, Boyd S, Hoover K, Meruvia-Pastor O, Gong M and Smith A. Augmented reality as a telemedicine platform for remote procedural training. Sensors (Basel) 2017; 17.

[61] Anvari M, Broderick T, Stein H, Chapman T, Ghodoussi M, Birch DW, McKinley C, Trudeau P, Dutta S and Goldsmith CH. The impact of latency on surgical precision and task completion during robotic-assisted remote telepresence surgery. Comput Aided Surg 2005; 10: 93-99.

[62] Kumcu A, Vermeulen L, Elprama SA, Duysburgh P, Platisa L, Van Nieuwenhove Y, Van De Winkel N, Jacobs A, Van Looy J and Philips W. Effect of video lag on laparoscopic surgery: correlation between performance and usability at low latencies. Int J Med Robot 2017; 13.

[63] Trivisonno R, Condoluci M, An X and Mahmoodi T. MIoT slice for 5G systems: design and performance evaluation. Sensors (Basel) 2018; 18.

[64] Nkenyereye L, Kwon J and Choi YH. Secure and lightweight cloud-assisted video reporting protocol over 5G-enabled vehicular networks. Sensors (Basel) 2017; 17.