Future Healthcare Journal 2022 Vol 9, No 1: 67–74 REVIEW

DIGITAL TECHNOLOGY

Digital tools in neurosurgical pathways: considerations for the future

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ABSTRACT

With aspects of neurosurgery becoming increasingly digitised, there is a need to understand both the prevalence and impact of digital tools on clinical and organisational outcomes. Consequently, we sought to evaluate evidence of the use of digital tools in neurosurgical settings. We systematically searched three public databases for relevant articles: 283 articles were screened using inclusion/exclusion criteria, with 26 selected for further analysis. Many studies reported on the use of simulation, smartphones, telemedicine and robotics in neurosurgical pathways from education through to postoperative care. Though generally beneficial for both patient and organisational outcomes, a number of considerations were highlighted. Many referred to protection of patient data, cost and requirements to ensure socially disadvantaged groups are not further excluded by the move to digital services. Fortunately, with further innovation, many of these limitations look set to dissipate over coming years, paving the way for a more streamlined neurosurgical pathway.

KEYWORDS: digital health, neurosurgery, telehealth, communication, data

DOI: 10.7861/fhj.2021-0163

Introduction

As with many industries, healthcare services have demonstrated rapid technological advancements in recent years. Patient records, previously confined to paper files and print-outs, are increasingly electronic, while vital signs, no longer the sole domains of professionals themselves, have become the focus of remote monitoring systems and smartphone apps.[1] This digitisation of an industry known for its rigidity is symptomatic of the need for greater efficiency, interconnectedness and data-driven decisions if we are to care for both growing and ageing populations. As a result, digital health, defined as the use of digital technologies (such as computing platforms, connectivity, software and sensors) for healthcare and related uses, has become the buzzword of 21st century medicine.[2]

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While broad, one such example of this transformation has centred around surgery, particularly neurosurgical patient pathways. Here, with the influx of mHealth apps, digital communications, machine learning tools and telehealth, patients stand to benefit from greater access and predictive tools in their diagnosis, monitoring and even time spent in theatre.[3] If we are to realise these benefits, however, a number of key considerations must be made in the development and adoption of such systems. Consequently, we sought to review existing literature in order to highlight both the benefits of digital communication tools in optimising neurosurgical patient pathways and the necessary steps to ensure their success.

Methods

Study design

The identification and reporting of the articles and their data included in this study were done under the guidance of the PRISMA checklist.[4] For the purpose of this study, we defined digital health tools as digital programs and devices intended for use within a medical pathway, including but not limited to smartphone applications, telemedicine, wearables and digital communication systems.

Search strategy and article selection

We searched the PubMed, SCOPUS and Cochrane Library databases for original research articles published since 01 January 2007 describing the use of digital health tools within a neurosurgical setting. Search terms included: ('Tele*' OR 'Virtual' OR 'Robotic' OR 'Digital') AND 'Neurosurg*' AND ('Data' OR 'Communication' OR 'Tools' OR 'Device' OR 'System'). In SCOPUS, this was limited to the article titles. Abstracts and full texts of returned articles were then screened for relevance and applied against the following inclusion criteria: studies evaluating use of one or more digital tools in a clinical neurosurgical setting, and studies provided qualitative or quantitative outcomes. Studies were excluded if in a non-English language, full text was unavailable, or measured outcomes consisted of biochemical and/or bioinformatics data. Article selection was independently approved by two authors of this study.

Results

This search strategy yielded 281 articles, with subsequent selection processes depicted in Fig 1. A further eight articles were identified through searching the reference lists of relevant

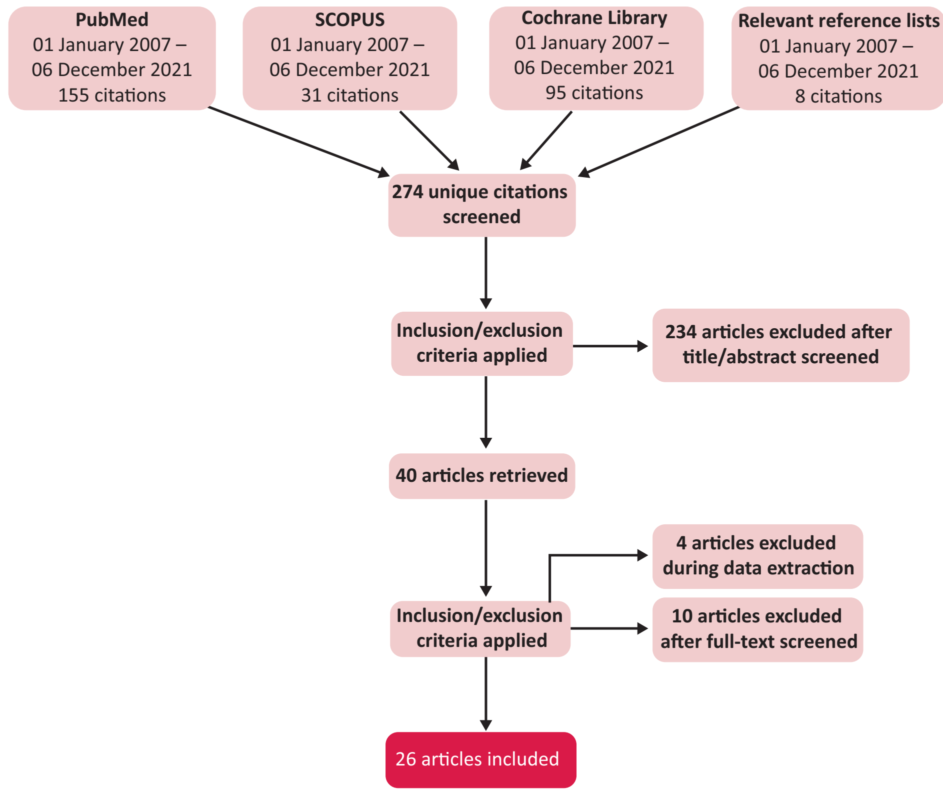

Fig 1. Study search strategy.

studies. Two-hundred and thirty-four of these were eliminated through abstract screening and a further 14 were eliminated following review of the full text or evaluation of study data. The remaining 26 studies are summarised in Table 1.[5–30] Eighteen of these articles were published in neurosurgical journals with the remaining eight published in neuroscience, emergency medicine, paediatric and rhinology journals. Ten studies included use of simulation/digital models as a digital tool, while six included telemedicine, three included robotics and four covered remote programming. Most of these studies referred to digital tools as a means of improving surgical training, while a further 11 considered digital tools predominantly as means of optimising pre-operative assessment and planning and five reviewed these tools in the context of postoperative care. Five studies examined the use of digital tools perioperatively. All included studies found digital tools to have a positive impact on aspects of either clinical or organisational outcomes.

Simulation and digital models

Ten of the articles reviewed in this study (38.46%) sought to evaluate the use of simulation or digital models in neurosurgical settings. These were predominantly education based. Studies by Bairamian *et al* and Breimer *et al*, for example, evaluated the use of virtual-reality against physical 3D models in the education of neurosurgical trainees.[8,9] Here, Bairamian *et al* developed 3D-printed and virtual angiography models, finding the latter to produce a statistically significant advantage in ability to zoom, resolution, ease of manipulation, model durability and educational potential. Trainees similarly found the virtual models more engaging, and allowed improved understanding of spatial anatomy, results supported by the work of Stepan *et al* in which study participants found virtual models to provide increased engagement, motivation and satisfaction compared with conventional teaching.[25] Breimer *et al*, however, in conducting simulated endoscopic third ventriculostomy on both virtual and physical models, reported lower instrument handling and procedural content scores for virtual vs physical models.[9] Similarly, both studies demonstrated physical 3D models offer significant advantages in depth perception over virtual equivalents.

Two further studies sought to evaluate the use of digital 3D models as educational tools. Such models, as reported by Stepan *et al* and de Notaris *et al*, were generated from computed tomography (CT) and shown to aid in both spatial understanding of cerebral anatomy and quantifying intra-operative bone removal compared with physical teaching methods.[11,25] Similar tools, such as VizDexter and the Atlas of Neurosurgery, provide both procedural and theoretical education.[31,32] Trainees, noting the digital tools to have greater practicality, reported increased motivation and improved procedural understanding. Significantly, however, in comparing digital teaching methods with conventional textbook education, Stepan *et al* found that there was no significant difference in clinical anatomy knowledge between the two groups on pre-intervention, post-intervention or retention quizzes, indicating virtual reality (VR) and digital models may confer more practical than theoretical benefits.[25]

In addition to its use in education, simulation and digital models have also found a significant role in pre-operative planning. Our search returned three articles using such tools for the analysis of surgical approaches or to model device placement. One such

Table 1. Summary of included studies

Study	Digital tool evaluated	Area of application	Outcome	Limitations
Alaraj *et al*, 2015[5]	Simulation/digital models	Education and preoperative planning	3D anatomical details closely resembled real operative anatomy and were useful in guiding surgical approaches	Few found the haptic feedback to closely resemble surgical procedures
Alsofy *et al*, 2020[6]	Simulation/digital models	Pre-operative planning	Improved detection of aneurysm-related vascular structures and appropriate surgical approaches	May tempt surgeons to neglect a wider array of approaches
Ashkenazi *et al*, 2015[7]	Telemedicine	Pre-operative planning	Reduced number of institutional transfers	None described
Bairamian *et al*, 2019[8]	Simulation/digital models	Education	VR angiography improved resolution, ease of manipulation, model durability and educational potential	Poorer depth perception
Breimer *et al*, 2017[9]	Simulation/digital models	Education	Relative VR benefits with respect to realistic representation of intraventricular anatomy	Reduced overall instrument handling and procedural content
de Almeida *et al*, 2020[10]	Smartphone applications	Perioperative	High accuracy and reliability of stereotactic brain biopsy coordinates	Certain features of interest are not available
de Notaris *et al*, 2011[11]	Simulation/digital models	Pre-operative planning	Improved quantification of intraoperative bone removal	Time consuming, not available intraoperatively, lack of depth perception
de Notaris *et al*, 2010[12]	Simulation/digital models	Pre-operative planning	Improved quantification of intraoperative bone removal	Time consuming, not available intraoperatively, lack of depth perception
Dong *et al*, 2018[13]	Simulation/digital models	Education	High reported fidelity, high user satisfaction and perceived usefulness	None described
Fan *et al*, 2020[14]	Robotics	Perioperative	Significantly improved screw-placement accuracy, reduced operative blood loss and length of stay	Learning curve required, unclear infection control protocol
Hou *et al*, 2016[15]	Smartphone applications and simulation/digital models	Pre-operative planning	High accuracy in predicting basal ganglia haematoma location	No error checking or location information during surgery
Latifi *et al*, 2018[16]	Telemedicine	Pre-operative planning	Decreased need for institutional transfer	Challenges with initial cost, integration
Li *et al*, 2017[17]	Remote programming	Postoperative care	Significant decreases seen in UPDRS scores	None described
Ma *et al*, 2021[18]	Remote programming	Postoperative care	Rapid symptom relief, institutional cost savings	Lack of physical examination data
Macyszyn *et al*, 2013[19]	Telemedicine	Electronic patient records and interdepartmental communication	Cost savings through elimination of repeat imaging requests	Increased operational complexity for departmental staff

Table 1. Summary of included studies (Continued)

Study	Digital tool evaluated	Area of application	Outcome	Limitations
Mandel *et al*, 2018[20]	Smartphone applications	Perioperative	Enhanced surgical mobility	None described
Mendez *et al*, 2013[21]	Remote programming	Postoperative care	High levels of patient and clinician satisfaction	No benefit in accuracy of programming or rate of adverse events
Moya *et al*, 2010[22]	Telemedicine	Pre-operative planning	Decrease in patient transfer requests	None described
Olldashi *et al*, 2019[23]	Telemedicine	Pre-operative planning	Improved access to care, decreased institutional transfer for low-risk patients	Initial set-up costs
Shibata, 2011[24]	Telemedicine	Pre-operative diagnosis/ planning	Earlier diagnosis of cerebral contusions, earlier escalation; improved planning time prior to emergency surgical intervention	Increased workload for consultant neurosurgeons
Stepan *et al*, 2017[25]	Simulation/digital models	Education	Increased engagement, motivation and satisfaction compared with conventional teaching	No improvement in clinical knowledge scores
Thapa *et al*, 2016[26]	Smartphone applications	Pre-/postoperative care, interdepartmental communication and education	Reduced time taken to interpret clinical images, improved intra-team and interdisciplinary communication	Significant discrepancies in image interpretation, greater risk of misuse of patient data
Wong *et al*, 2007[27]	Simulation/digital models	Education / pre-operative planning	Users gained a better understanding of the best approach for microsurgical clipping for the patient	None described
Xu *et al*, 2020[28]	Remote programming	Postoperative care	Significant improvement in UPDRS-III; 89.29% of patients were satisfied or very satisfied	Reduced opportunity for physician-led physical examination to assess changes in muscle tone
Zappa *et al*, 2019[29]	Robotics	Perioperative	Improved completion times in bimanual tasks, decreased surgical fatigue	Results indicated more difficulty and higher fatigue in simple grasping tasks
Zhang *et al*, 2019[30]	Robotics	Perioperative	Increased accuracy of screw placement, decreased radiation doses, reduced rate of screw revisions	Greater learning curve, not necessarily more effective in completion of simple tasks, variable mental fatigue scores

UPDRS = Unified Parkinson's Disease Rating Scale; VR = virtual reality.

article by Wong *et al* studied the clipping of intracranial aneurysms in a stereoscopic virtual reality environment.[27] Here both CT angiography and aneurysm clip data was uploaded to a virtual workstation and used to simulate clip placement from an array of different approaches, allowing surgeons to better understand potential exposure and obliteration of an aneurysm. Further work by Dong *et al* and Alaraj *et al* built on this, adding in real-time haptic feedback and concluding that these tools provided a close resemblance to real operative anatomy and accurate guidance for deciding surgical approaches.[5,13] A similar study by Alsofy *et al* again used CT angiography to develop anatomically accurate 3D models of 26 pre-operative patients. In this case, authors concluded that 3D-VR significantly aided detection of aneurysm-related vascular structures, recommended head positioning and optimum surgical approaches. As a result, though it may be more time intensive than conventional methods, it is evident that reconstruction of pre-operative scans into spatially representative 3D-VR models enables greater understanding of patient pathology and aids operational strategy.

Telemedicine and real-time digital image transfer

Having already influenced the education of neurosurgical trainees, other digital tools have optimised approaches to diagnosis and pre-/postoperative patient monitoring. Some of these, described as digital health communication tools (DHCTs), have been implemented in the diagnostic and pre-operative setting, centred around telemedicine, data transfer and image review at times when consultant neurosurgeons are less available. Here, by providing greater access to senior decision makers, whether intra- or inter-institutional, digital tools have demonstrated improvements in clinical workloads and even postoperative patient outcomes.

Subsequently, six studies were found to include use of telemedicine and/or digital image transfer services. Four of these studies specifically examined the effect of such services on triage, review and resulting rates of patient transfer. Olldashi *et al* and Latifi *et al* specifically analysed results of 590 and 146 neurology patients, respectively, all of whom had been referred to a level 1 trauma centre for neurosurgical tele-review.[16,23] Patients were subsequently reviewed by neurosurgical consultants and transferred according to clinical risk. Through this telemedicine service, the two studies showed rates of transfer to the tertiary care centre at just 31% and 34%, respectively, highlighting the use of telemedicine and digital image transfer in providing clinical assurance for low-risk cases and preventing costly and unnecessary patient transfers. These results were mirrored by similar studies from Moya *et al* and Shibata, the former of which demonstrated a 25% reduction in patient transfer requests following implementation of virtual consultant review.[22,24] Unsurprisingly, a common limitation of this technology noted by the authors was the lack of physical examination data reducing the information available to physicians and clinical decision makers, though available data was still considered sufficient to make appropriate transfer decisions. Ashkenazi *et al*, in analysing the results of 526 patients in a level 2 centre, concluded that selected patients with head trauma may be safely managed in a level 2 trauma centre following virtual neurosurgical review.[7] Consequently, greater adoption of telemedicine technologies in a ‘hub and spoke’ distribution between major neurotrauma centres and regional hospitals may produce significant cost savings and limit the need for patient transfer for both low- and moderate-risk cases.

The findings of these studies in the use of telemedicine and image transfer are supported by the work of Nanah and Bayoumi.[33] These authors, in conducting a systematic review on the topic of DHCTs, returned 13 studies evaluating the use of neurosurgical DHCTs in both interventional and non-interventional settings. The authors subsequently highlighted the use of telemanipulation and telementoring, concluding that digital input was beneficial in all observed cases, particularly in allowing successful completion of otherwise excessively challenging or complicated interventions.[34,35]

Smartphone applications

Of the 26 returned articles, a further four examined the use of smartphone, or mHealth, applications. De Almeida *et al* evaluated the accuracy and reliability of the StereoCheck app in providing stereotactic coordinates during brain biopsies.[10] In using exported patient images, the app demonstrated promising accuracy of 0.82 ± 0.61 mm as well as high consistency between progressive measurements. Hou *et al* similarly utilised smartphone applications to provide an augmented reality (AR) technique that could localise hypertensive haematomas in the basal ganglia.[15] AR markers were derived from processed CT from the patient in question. Subsequently, actual haematoma locations were verified intraoperatively, demonstrating sufficient accuracy and reliability of the AR method. Notably, both of these tools lacked specific features calculating the skull entry point and needle trajectory. Mandel *et al* evaluated a smartphone-compatible endoscope for minimally-invasive surgery, finding the tool to improve surgical mobility and allow a more intuitive movement compared with traditional neuroendoscopy.[20]

Thapa *et al* instead studied the use of multiple smartphone applications through the neurosurgical pathway.[26] Here, the authors concluded these tools to aid quick reliable decision making, allowing for instantaneous communication, storing data and knowledge exchange, though they brought with them increased risk of data misuse and increased discrepancies in clinical image interpretation.

Robotics and direct digital interventions

As an example of direct digital interventions, robotic and robotic-assisted surgery has gained significant traction over recent years. Our search consequently yielded three articles evaluating the use of robotic and robotic-assisted neurosurgery. Two of these studies (Fan *et al* and Zhang *et al*) specifically examined the use of such tools in spinal surgery, while a third (Zappa *et al)* looked at endoscopic skull-base surgery.[14,29,30] Fan *et al* assigned 135 patients with newly diagnosed cervical spinal disease and who required screw fixation to either a robotic-assisted or a fluoroscopy-assisted group, finding the robotic-assisted interventions to reduce blood loss, length of stay and improve the accuracy of surgical screw placement.[14] Duration of procedure did not differ between the two groups, though the learning curve required to become proficient in robotic-assisted surgery was considered to be significant. Zhang *et al* reported near identical outcomes, with increased accuracy of screw placement and prior training being a key measure of success.[30] Zappa *et al,* on the other hand, required 30 neurosurgeons to complete two practical procedures, with and without assistance of an endoscopic robot, demonstrating a trend toward better completion times and efficacy in the bimanual task when performed with the robot.[29] According to the modified National Aeronautics and Space Administration Task Load Index test, surgeons felt more successful with the robot, finding it less stressful and mentally demanding. Robotic assistance, however, was noted to have a negative effect on mental fatigue when used in the simple grasping task compared with conventional methods. As a result, it is clear the impact of robotic assistance on both clinical outcomes and human factors need to be further assessed, however, they are likely to have a growing role in more complicated, bimanual surgical procedures.

Remote monitoring and remote programming

Four of the included studies explored the use of remote programming in postoperative care. Three of these articles specifically evaluated remotely programmed deep-brain stimulation (DBS) in the treatment of Parkinson's disease (PD), while one article included patients with essential tremor and cervical dystonia. Li *et al*, for example, studied the efficacy and safety of wirelessly programmed DBS of bilateral subthalamic nucleus (STN) in patients with primary PD.[17] DBS was activated 1 month postoperatively, with 3-month follow-up showing significant decreases in Unified Parkinson's Disease Rating Scale (UPDRS) motor scores. These findings were supported by those of Xu *et al*, demonstrating significant improvements in the UPDRS-III scores of 26 patients following onset of remote DBS programming and high rates of satisfaction with the remote system.[28] An additional study by Ma *et al* found significant time and cost savings through reduced outpatient visits, as well as high patient satisfaction, while a feasibility study by Mendez *et al* demonstrated non-experienced personnel to competently programme the remote DBS system following a single training session.[18,20] Notably, however, the use of such remote tools limits opportunity for physical examination and, as such, may reduce the quality of data (such as muscle tone) needed to make informed decisions about patient care. Similarly, while many of these systems meet current clinical standards, few are yet to show clinical advantages over non-remote programming of DBS.

Discussion

Ultimately, these papers highlight clear diagnostic advantages when utilising digital tools in a neurosurgical setting. By identifying those at increased risk of decompensation and escalating this appropriately prior to pre-operative admission, clinicians stand to reduce surgical cancellations, improve patient outcomes and provide organisational benefits through cost savings and reduced time lost. Meanwhile, through use of neurosurgical simulations in surgical training, and the assistance of robotics and AR in the operative settings, such tools have potential to improve surgical outcomes.

Barriers to implementation

Despite these benefits, however, a number of significant and persistent barriers remain. Many current healthcare staff, for example, lack the skills with which to safely adopt digital tools. This lack of digital literacy, highlighted in the Topol review, risks unnecessary clinical errors and novel ethical challenges, particularly when handling novel, continuous patient data.[37] Work from Macyszyn *et al*, for example, highlighted the impact of an institutional telemedicine and picture archiving and communication system, shifting data handling from clinical to managerial staff, resulting in an inadvertent increase in the number of accidental data breaches.[19] Institutions may, therefore, require a greater focus on digital skills at both graduate and undergraduate levels if we are to safely implement digital tools across the neurosurgical pathway, something recently realised as part of Health Education England's digital competencies framework.[38]

Concerns also exist around the potential widening of healthcare equalities. Many of those already subject to social exclusion and, thus, poor health outcomes are also subject to digital exclusion, resulting from decreased access to the internet and other digital services.[39] This can include those in financial difficulty, older individuals who are less likely to own a smartphone as well as those geographically excluded, particularly from rural communities. Though ethnic disparities do exist, these are explained by the discrepancies between age and income profiles between each group. There is, however, insufficient evidence in the way different social groups engage with digital technologies (for health and other purposes) in which the concepts of digital and/or health literacy, as well as trust and privacy concerns, are likely to be important in the success of digital health initiatives.[39] Simple measures of use and access cannot account for these. There is consequently a need to not only ensure greater access to digital technologies, either through free market competition, or concerted efforts from health providers to ensure those with reduced access are appropriately enabled to access digital services. Similarly, efforts to improve digital literacy must not be limited to healthcare professionals, and must be extended to patients and their families wherever possible.

Finally, and perhaps most importantly, cost is seen as a significant barrier to adoption of these systems. 3D models, highlighted herein, are significantly more expensive on a case-by-case basis than conventional equivalents, particularly when personalised to specific procedures or specific patient pathology.[13] Importantly, however, this is not uniformly the case when adopting digital platforms and a number of studies, including those by Thapa *et al* and Macyszyn *et al*, have demonstrated considerable net savings.[19,26] This has typically been through either low upfront costs associated with communication tools or organisational savings attributed to improved clinical outcomes or preventing the need for duplicate investigations, as is often the case in current clinical practice.

Direction of future developments

Fortunately, with careful consideration of the earlier challenges, digital technologies are likely to play increasingly broad roles in the neurosurgical patient pathway, with current digital applications (such as remote patient monitoring (RPM), telemedicine and image transmission) likely to be adopted in order to both improve patient outcomes and increase the efficiency and cost-effectiveness of patient care. These technologies, such as remote monitoring devices, are largely patient driven. As a result, further innovation will likely provide cheaper and more accessible products than are currently available, or even possible. Furthermore, alongside the development of mHealth applications, such as Apple Health and AI-driven data analysis tools, these devices are likely to become increasingly connected and automated for ease of interpretation.[40] This will be particularly useful in rural areas where availability of consultant neurosurgeons is low.

Telemedical encounters in neurosurgery are also being increasingly adopted, particularly in resource-scarce times such as the pandemic.[36] Fortunately, these platforms have been more widely adopted in resource-poor countries than previously expected, as well as in medically underserved areas with poor access to neurosurgical technologies. Although further large-scale studies are required, there is overwhelming evidence to suggest that remote telemedical patient visits are promising in both inpatient and outpatient settings. With the main barrier to widespread adoption of telemedicine in neurosurgery reported to be due to technological failures during consultation; then technological familiarity, improved connectivity and more streamlined user interfaces will no doubt increase the utilisation of telemedicine in the hospital setting.

Conclusion

It is clear that these platforms offer tangible benefits for both patients and professionals. Provided they are carefully implemented, with appropriate training of staff, digital tools promise to make neurosurgical patient pathways increasingly convenient, efficient and consistent, while at the same time offer a personalised level of care that has been so far unavailable in all but a few care settings. ■

Conflicts of interest

Alexander Deighton and Debashish Das report paid involvement in Ortus-iHealth, a virtual outpatients' platform, that may be affected by the subject matter or materials discussed in this manuscript.

References

1 Mosnaim GS, Stempel H, Van Sickle D, Stempel DA. The adoption and implementation of digital health care in the post–COVID-19 era. *J Allergy Clin Immunol Pract* 2020;8:2484–6.
2 US Food and Drug Administration. *What is digital health?* US FDA, 2021. www.fda.gov/medical-devices/digital-health-center-excellence/what-digital-health [Accessed 07 December 2021].
3 Vaghefi I, Tulu B. The continued use of mobile health apps: insights from a longitudinal study. *JMIR mHealth and uHealth* 2019;7:e12983.
4 Page MJ, McKenzie JE, Bossuyt PM *et al*. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 2021;372:n71.
5 Alaraj A, Luciano CJ, Bailey DP *et al*. Virtual reality cerebral aneurysm clipping simulation with real-time haptic feedback. *Operative Neurosurgery* 2015;11:52–8.
6 Zawy Alsofy S, Sakellaropoulou I, Nakamura M *et al*. Impact of virtual reality in arterial anatomy detection and surgical planning in patients with unruptured anterior communicating artery aneurysms. *Brain Sciences* 2020;10:963.
7 Ashkenazi I, Zeina AR, Kessel B *et al*. Effect of teleradiology upon pattern of transfer of head injured patients from a rural general hospital to a neurosurgical referral centre: follow-up study. *Emerg Med J* 2015;32:946–50.
8 Bairamian D, Liu S, Eftekhar B. Virtual Reality angiogram vs 3-dimensional printed angiogram as an educational tool—a comparative study. *Neurosurgery* 2019;85:E343–9.
9. Breimer GE, Haji FA, Bodani V *et al*. Simulation-based education for endoscopic third ventriculostomy: a comparison between virtual and physical training models. *Operative Neurosurgery* 2017;13:89–95.
10 de Almeida JC, Dellaretti M, Ferreira PH *et al*. Evaluation of accuracy and reliability of a smartphone stereotactic coordinates checking application. *World Neurosurgery* 2020;141:e324–33.
11 de Notaris M, Solari D, Cavallo LM *et al*. The use of a three-dimensional novel computer-based model for analysis of the endonasal endoscopic approach to the midline skull base. *World Neurosurgery* 2011;75:106–13.
12 de Notaris M, Prats-Galino A, Cavallo LM *et al*. Preliminary experience with a new three-dimensional computer-based model for the study and the analysis of skull base approaches. *Child's Nervous System* 2010;26:621–6.
13 Dong M, Chen G, Qin K *et al*. Development of three-dimensional brain arteriovenous malformation model for patient communication and young neurosurgeon education. *Br J Neurosurg* 2018;32:646–9.
14 Fan M, Liu Y, He D *et al*. Improved accuracy of cervical spinal surgery with robot-assisted screw insertion: a prospective, randomized, controlled study. *Spine* 2020;45:285–91.
15 Hou Y, Ma L, Zhu R, Chen X. iPhone-assisted augmented reality localization of basal ganglia hypertensive hematoma. *World Neurosurgery* 2016;94:480–92.
16 Latifi R, Olldashi F, Dogjani A *et al*. Telemedicine for neurotrauma in Albania: initial results from case series of 146 patients. *World Neurosurgery* 2018;112:e747–53.
17 Li D, Zhang C, Gault J *et al*. Remotely programmed deep brain stimulation of the bilateral subthalamic nucleus for the treatment of primary Parkinson disease: a randomized controlled trial investigating the safety and efficacy of a novel deep brain stimulation system. *Stereotact Funct Neurosurg* 2017;95:174–82.
18 Ma Y, Miao S, Zhou R *et al*. Application of remote deep brain stimulation programming for Parkinson's disease patients. *World Neurosurgery* 2021;147:e255–61.
19 Macyszyn L, Lega B, Bohman LE *et al*. Implementation of a departmental picture archiving and communication system: a productivity and cost analysis. *Neurosurgery* 2013;73:528–33.
20 Mandel M, Petito CE, Tutihashi R *et al*. Smartphone-assisted minimally invasive neurosurgery. *Journal of Neurosurgery* 2018;130:90–8.
21 Mendez I, Song M, Chiasson P, Bustamante L. Point-of-care programming for neuromodulation: a feasibility study using remote presence. *Neurosurgery* 2013;72:99–108.
22 Moya M, Valdez J, Yonas H, Alverson DC. The impact of a telehealth web-based solution on neurosurgery triage and consultation. *Telemed J E Health* 2010;16:945–9.
23 Olldashi F, Latifi R, Parsikia A *et al*. Telemedicine for neurotrauma prevents unnecessary transfers: an update from a nationwide program in Albania and analysis of 590 patients. *World Neurosurg* 2019;128:e340–6.
24 Shibata Y. A remote desktop-based telemedicine system. *J Clin Neurosci* 2011;18:661–3.
25 Stepan K, Zeiger J, Hanchuk S *et al*. Immersive virtual reality as a teaching tool for neuroanatomy. *Int Forum Allergy Rhinol* 2017;10:1006–13.
26 Thapa A, Bidur KC, Shakya B. Cost effective use of free-to-use apps in neurosurgery (FAN) in developing countries: from clinical decision making to educational courses, strengthening health care delivery. *World Neurosurgery* 2016;95:270–5.
27 Wong GK, Zhu CX, Ahuja AT, Poon WS. Craniotomy and clipping of intracranial aneurysm in a stereoscopic virtual reality environment. *Neurosurgery* 2007;61:564-9.
28 Xu J, Wang J, Keith S *et al*. Management of Parkinson's disease patients after DBS by remote programming: preliminary application of single center during quarantine of 2019-nCoV. *Journal of Neurology* 2021;268:1295–303.
29 Zappa F, Mattavelli D, Madoglio A *et al* Hybrid robotics for endoscopic skull base surgery: preclinical evaluation and surgeon first impression. *World Neurosurgery* 2020;134:e572–80.
30 Zhang Q, Han XG, Xu YF *et al*. Robot-assisted versus fluoroscopy-guided pedicle screw placement in transforaminal lumbar interbody fusion for lumbar degenerative disease. *World Neurosurgery* 2019;125:e429–34.
31 Robison RA, Liu CY, Apuzzo ML. Man, mind, and machine: the past and future of virtual reality simulation in neurologic surgery. *World Neurosurgery* 2011;76:419–30.
32 Teton ZE, Freedman RS, Tomlinson SB *et al*. The Neurosurgical Atlas: advancing neurosurgical education in the digital age. *Neurosurgical Focus* 2020;48:E17.
33 Nanah A, Bayoumi AB. The pros and cons of digital health communication tools in neurosurgery: a systematic review of literature. *Neurosurgical Review* 2020;43:835–46.
34 Mendez I, Hill R, Clarke D, Kolyvas G, Walling S. Robotic long-distance telementoring in neurosurgery. *Neurosurgery* 2005;56:434–440.
35 Tian Z, Lu W, Wang T *et al*. Application of a robotic telemanipulation system in stereotactic surgery. *Stereotact Funct Neurosurg* 2008;86:54–61.

36 De Biase G, Freeman WD, Bydon M *et al*. Telemedicine utilization in neurosurgery during the COVID-19 pandemic: a glimpse into the future? *Mayo Clin Proc Innov Qual Outcomes* 2020;4:736–44.
37 Topol E. *The Topol Review: Preparing the healthcare workforce to deliver the digital future*. NHS Health Education England, 2019.
38 Oberländer M, Beinicke A, Bipp T. Digital competencies: A review of the literature and applications in the workplace. *Comput Educ* 2020;146:103752.
39 Honeyman M, Maguire D, Evans H, Davies A. *Digital technology and health inequalities: a scoping review*. Public Health Wales, 2020.
40 Jung SY, Kim JW, Hwang H *et al*. Development of comprehensive personal health records integrating Patient-Generated health data directly from Samsung S-Health and apple health Apps: retrospective cross-sectional observational study. *JMIR mHealth and uHealth* 2019;7:e12691.

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