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. 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.

Authors: Alexander J Deighton, Alexander J Deighton, Karanjot Chhatwal and Debashish Das

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. 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. 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
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. 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. 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. 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. 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. Similar tools, such as VizDexter and the Atlas of Neurosurgery, provide both procedural and theoretical education. 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.

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
| 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                    |
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

| Study                  | Digital tool evaluated       | Area of application | Outcome                                                                 | Limitations                                      |
|------------------------|-----------------------------|---------------------|-------------------------------------------------------------------------|-------------------------------------------------|
| Mandel et al, 201820   | Smartphone applications     | Perioperative       | Enhanced surgical mobility                                              | None described                                   |
| Mendez et al, 201321   | 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, 201022     | Telemedicine                | Pre-operative planning | Decrease in patient transfer requests                                   | None described                                   |
| Ollidashi et al, 201923| Telemedicine                | Pre-operative planning | Improved access to care, decreased institutional transfer for low-risk patients | Initial set-up costs                             |
| Shibata, 201124        | 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, 201725   | Simulation/digital models   | Education           | Increased engagement, motivation and satisfaction compared with conventional teaching | No improvement in clinical knowledge scores       |
| Thapa et al, 201626    | 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, 200727     | 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, 202028       | 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, 201929    | 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, 201930    | 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 |

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UPDRS = Unified Parkinson’s Disease Rating Scale; VR = virtual reality.
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. Oldashi 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 neurological 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.29,30 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. 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. 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. 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. 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. 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. Concerns also exist around the potential widening of healthcare inequalities. 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. 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. 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. 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. 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. 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. 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.
Digital tools in neurosurgical pathways

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.

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Address for correspondence: Alexander Deighton, Barts and the London School of Medicine and Dentistry, Garrod Building, Turner Street, London E1 2AD, UK.
Email: a.deighton@smd17.qmul.ac.uk
Twitter: @AlexJDeighton