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Evolution and Revolution of Imaging Technologies in Neurosurgery

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Abstract

We understand only a small fraction of the events happening in our brains; therefore, despite all the progress made thus far, a whole array of questions remains. Nonetheless, neurosurgeons invented new tools to circumvent the challenges that had plagued their predecessors. With the manufacturing boom of the 20th century, technological innovations blossomed enabling the neuroscientific community to study and operate upon the living brain in finer detail and with greater precision while avoiding harm to the nervous system. The purpose of this chronological review is to 1) raise awareness among future neurosurgeons about the latest advances in the field, 2) become familiar with innovations such as augmented reality (AR) that should be included in education given their ready applicability in surgical training, and 3) be comfortable with customizing these technologies to real-life cases like in the case of mixed reality.

Keywords: augmented reality, history, neurosurgery, technologies, imaging

Introduction

The field of neurosurgery is such an intricated environment where we understand only a small fraction of the events happening in our brains with a whole array of questions remaining. Modern medicine began in 1543 with the first milestone "*De Humanis Corporis Fabrica Libri Septem*" by Andreas Vesalius (1514-1564). At that time, the diagnosis and treatment of neurological diseases were difficult because of the minimal accessibility of the brain through the skull. Furthermore, the amount of brain tissue required to be damaged to reach these deep, critical structures rendered many diseases inoperable.

Nevertheless, neurosurgeons invented new tools to circumvent the challenges that had plagued their predecessors. With the advent of radiology and the manufacturing boom of the 20th century, technological innovations blossomed in the 20th and 21st centuries and have enabled the neuroscientific community to study and operate upon the living brain in finer detail and greater precision while avoiding harm to the nervous system. The numerous Nobel Prizes granted (Fig. 1) revolutionized our neurosurgery field improving diagnosis, treatment, and patient outcomes.

The purpose of this historical vignette is to 1) raise awareness among future neurosurgeons about the latest advances in the field, 2) become familiar with innovations such as AR that should be included in education given their ready applicability in surgical training, and 3) be comfortable with customizing these technologies to real-

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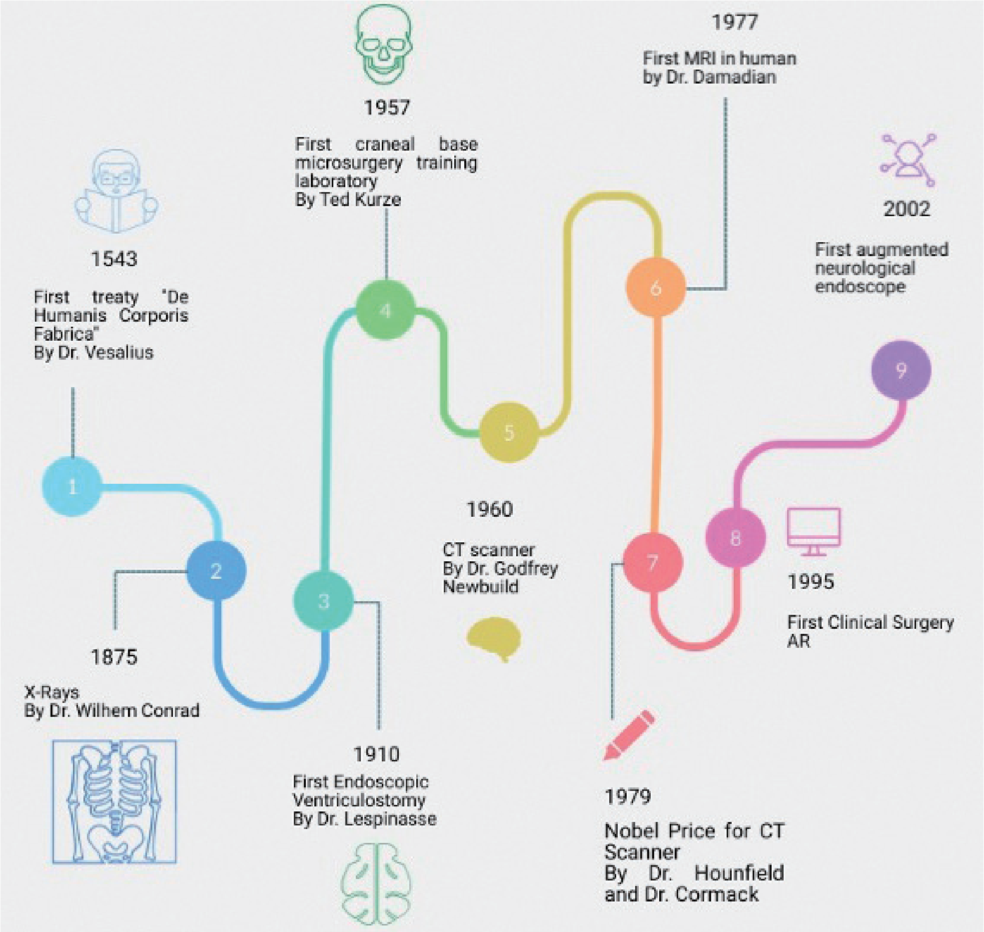

Fig. 1 **Time points of some historical technological progresses that have influenced neurosurgery.**

life cases like in the case of mixed reality.

Methods

We search in platforms such as Pubmed and Google Scholar for the top cited manuscripts based on the keywords technology AND neurosurgery AND history. A fourth keyword was added according to imaging tools used in neurosurgery (i.e., X-ray, computed tomography (CT), magnetic resonance imaging (MRI), endoscopy, and AR). We did another search under the same criteria, including more technical and therapeutical studies (i.e., neuronavigation, microsurgery, and functional neurosurgery).

1. Looking at the macroscopic level

1.1. Beginning of technological neurosurgery-X-rays

X-rays are one of the most antique diagnosis tools for cranial and brain pathologies. In 1875, physicist and mechanical engineer Wilhelm Conrad Röntgen made it possible to look through the skull and other parts of the body in a noninvasive manner when he discovered a frequency of electromagnetic radiation to which soft tissues of the body were transparent. He named his discovery the "X-ray." This discovery started a revolution in medicine, allowing physicians to make diagnoses more accurately and precisely.[1-4)] Soon after Röntgen's discovery, Fredor Krause was the first neurosurgeon to adopt the use of X-ray imaging in his clinical practice. Kraus used this technique to study tumors at the base of the skull and to perform procedures such as ventricular drainages. In 1907, Krause published his revolutionary X-ray techniques in the first textbook of neurosurgery "*Chirurgie des Gehirns und Rückenmarks*."[5)]

Shortly after Krause's publications, Dr. Walter E. Dandy conceived the idea of injecting air through a lumbar puncture to visualize the ventricular system based on the work of his mentor Dr. Halsted, who considered the radiolucent effect of air in the gastrointestinal tract to identify intestinal obstructions. This procedure was named roentgenography of the brain, which was later called ventriculography.[6,7)]

Today, the resolution and availability to take radiographs have evolved dramatically to modern fluoroscopy systems that can take up to 30 captures per second, allowing surgical procedures in real time,[8)] such as the digital subtraction angiography, which was available worldwide since 1980.[9)]

1.2 Redefining X-rays toward higher resolution-CT

As medical imaging evolved with higher resolution radiographs, the interest in developing a technology that would allow visualization of soft tissue and structures inside the head increased. Some neurosurgeons, such as Harvey Cushing, started to recognize that X-rays were very limiting in the diagnosis of brain tumors and other pathologies.[10)]

In the decade of the 1960s, Godfrey Newbold Hounsfield developed the first useful prototype of a CT scanner, a device that can capture and build figures depending on the density of the tissues. Contemporaneously, Allan McLeod Cormack, at Tufts University in Boston, invented a method of CT scanning. These inventions granted Hounsfield and Cormack a Nobel Prize in Physiology or Medicine in 1979.[11-13)] This approach combines X-ray images with digital geometry processing to generate images of higher resolution.

James Ambrose, a radiologist at Atkinson Morley Hospital in London who worked with Hounsfield in scanning animal tissues and preserved human organs, led to the introduction of the first CT scanner at his hospital in 1971, thus generating the first human clinical results using a CT scanner.[11)] It is said that after scanning the head of a patient in the Wesley Pavilion of Northwestern Memorial Hospital in Chicago, Hounsfield was astonished and confused upon seeing an image of a hypertensive hematoma not seen before in such an improved definition.[14)]

1.3 Broadening the capabilities of brain imaging-MRI

The next revolution in neuroimaging started in 1946 when two groups of researchers (i.e., Bloch, Hansen, and Packarde at Stanford University and Purcell, Torrey, and Pound at Harvard University) registered the first clinical report on nuclear magnetic resonance.[15,16)] However, it was limited to nonhuman animals. In 1971, Raymond V. Damadian published in *Nature* the use of spin echo nuclear magnetic resonance measurements as a method for discriminating between malignant tumors and normal tissue.[17-19)] This roused the interest to apply this methodology to humans. In 1977, the first MRI scanner intended for human use was made by Damadian and his team at the University of Aberdeen. However, it was not until the 1980s that MRI was introduced for clinical practice.[20,21)]

Independently, Paul Lauterbur from the University of Illinois and Sir Peter Mansfield from the University of Nottingham discovered that introduction of gradients in the magnetic field creates two-dimensional images composited to make high-resolution 3D models of the subject.[22)] The development and use of the technology granted them the Nobel Prize in Physiology or Medicine in 2003. Surprisingly, Damadian was not included in the prestigious award. Damadian said in an interview with *Nature*, “If I had never been born, there would never be MRI today.”[23)]

1.4 Taking the brain images to the operating room-image-guided neuronavigation

Neurosurgeons are constantly exploring, planning, or modifying surgical techniques to approach the brain more safely. Therefore, the need of improving surgical accuracy drove Carl Dittmar in Germany (1873) and Dmitrii Zernov in Russia[24)] to create one of the first devices for stereotactic surgery.[25,26)] In 1908, Sir Victor Horsley and Robert H. Clarke introduced a more precise device, using Cartesian coordinates in monkeys.[27)] It took Ernest A. Spiegel and Henry T. Wycis almost five decades (1947) to translate the system in humans.[28)] Afterward, different stereotactic frames were designed. The most worldwide known were introduced by Leksell (1949), Todd-Wells (1965), Riechert-Mundinger (1951), and Brown-Robert-Wells (1980). Brown’s stereotactic head frame had the uniqueness of targeting the brain using a standard CT scanner computer.[29)] This became one of the primitive notions of image-guided neuronavigation. In 1987, Watanabe introduced a multijoint sensor arm connected to computer software that correlated preoperative CT images with the brain.[30)] A few years later, this concept led to a surgical frameless neuronavigation that remains until now.

1.5 Deeper steps into neuronavigation-radiosurgery and deep brain stimulation

Stereotactic neurosurgery opened significant and different options to treat intracranial lesions. In 1949, Leksell introduced the first arc-centered stereotaxic device, which could reach a target from any angle.[31)] That invention allowed him to pursue the first stereotactic radiosurgery, which consisted in using ionizing radiation in a specific affected area. Then, Leksell and Börje Larsson decided to try high-energy proton irradiation,[32)] but the complex requirements for clinical use led them to prefer working with gamma ray irradiation, making the Gamma Knife setup the first form of radiosurgery. This was followed by LINAC (Linear Accelerator), where a single X-ray beam rotates around the patient. Presently, Gamma Knife, LINAC, and most recently proton beam, are the three technologies most used worldwide for stereotactic radiosurgery.

Another essential role of stereotactic neurosurgery was deep brain stimulation (DBS). In 1960, Hassler et al. inserted electrodes in the deep brain of patients with motor disorders, and the outcome was promising showing long-term symptom improvement.[33)] Unfortunately, this stimulation needed to be constantly repeated because there were no definitive electrodes. However, in 1973, Yoshio Hosobuchi used definitive deep brain electrodes to treat a patient with facial pain.[34)] In the last decades, the design and setup configuration of different electrodes have expanded the DBS armamentarium.

2. What cannot be seen by the "naked eye"

2.1 Visualizing a microworld-surgical microscopy

Before the 1950s, surgeries were performed with the unaided eye; however, in 1952, Dr. H. Littmann made an enormous step into modern surgical practice when he modified a colposcope into a microscope that responded to most of the operational requirements. This device was known as the OPMI1.[35] This microscope was introduced at the Fifth International Congress of Otolaryngologists in Amsterdam. This microscope was able to magnify 4-25 times with undistorted depth perception and to provide an intensity of target illumination in the depth of a narrow field strong enough to obtain color motion pictures (3200-5000 footcandles). The average target light intensity with overhead lighting in neurosurgical fields was 800 footcandles. In 1957, Dr. Ted Kurze started to develop microsurgical techniques opening the first world cranial base microsurgery training laboratory.[36]

The advances in the surgical microscope and microneurosurgical instruments led to new procedures that revolutionized neurosurgery. These tools allowed Jacobson and Suarez to perform the first arterial replacement of small vessels in 1960.[27] Some months later, they made the first middle cerebral artery endarterectomy.[38,39]

Before 1966, the number of performed clipped aneurysms was reduced due to limited optics.[40,41] Since then, various neurosurgeons accomplished significant advances in microsurgery, with Dr. M. Gazi Yaşargil being one of the most renowned. He developed microneurosurgical techniques for cerebrovascular neurosurgery, approaching aneurysms through natural pathways of the cisternal systems.[42,43] He performed the first EC-IC bypass to bypass an occluded internal carotid artery.[44] Dr. Yaşargil also made great contributions to moyamoya disease, doing the first superficial temporal artery-middle carotid artery bypass (end-to-end STA to left insular MCA anastomosis).[45] He then invented the bipolar coagulation,[46] counterbalance "floating" microscope, self-retaining adjustable retractor, ergonomic aneurysms clips, and appliers that revolutionized the field.[47] Surgical microscopy was so relevant that in 1971 took place the first microsurgery symposium in Cincinnati, OH congregate several pioneers of microneurosurgey including Gazi Yaşargil, Albert L. Rhoton, Frank H. Mayfield, Jules Hardy, Peter J. Jannetta, and Leonard I. Malis.

2.2 Training the eye-microsurgical anatomy laboratory

Microsurgery was first implemented in 1954, at the 5th International Congress of Otorhinolaryngology in Amsterdam. A modified Hinselmann's colposcope[48] made by Dr. H. Littmann called OPMI-1. Nevertheless, microsurgery took almost 15 years to be integrated into the operating rooms. With the implementation of OPMI-1, near-impossible procedures such as cistern exploration and brain artery reconstruction became possible.[42]

Neurosurgeons such as M Gazi Yaşargil and Albert L. Rhoton were pioneers in this field. In 1975, Dr. Rhoton founded the famous Rhoton Lab at the University of Florida. This was one of the first microneurosurgical laboratories in a teaching hospital. This laboratory became a critical resource, enabling the generation of more than 500 articles for Neurosurgery journal, a neurosurgical textbook "*Cranial Anatomy and Surgical Approaches*" and a website with a compilation of anatomy neurological presentations "The Rhoton Collection," where brain anatomy and common variations of cadaveric specimens are described.[49] From the time the University of Florida laboratory opened until Dr. Rhoton's death on February 21, 2016, more than 120 research fellows from all over the world have trained at this laboratory.[50]

The art of surgery is becoming increasingly complex and dependent on scopes, screens, and technology, inviting a complex learning curve and development of hand-eye coordination and dexterity among other skills.[51] The development of microneurosurgical skills should be part of the educational goals of any neurosurgical resident or fellow to improve patient outcomes. Globally, countless neurosurgical programs have microsurgical anatomy laboratories that permit surgical training and increase manual dexterity to improve access to intracranial areas.[52]

Enhancing techniques such as surgical simulation, surgical robotics, 3D printing, 3D cameras, and advanced neuroimaging allow for the visualization and manipulation of surgical macrostructural and microstructural anatomy. These tools decrease the morbidity and mortality of neurological disease by allowing surgeons to treat patients more knowledgeably and precisely. Such are the legacies of great minds of neurosurgery.[53]

2.3 Making reachable the unreachable-endoscopy

The use of endoscopes has been intermittent in many operating rooms largely because their components have been historically difficult to use effectively. The xenon and halogen bulbs, lenses, flexible videoscopes, and their controls were cumbersome necessitating frequent troubleshooting. In 1910, Lespinasse-an American urologist-was the first to perform a choroid plexectomy. He performed endoscopic surgery on a pediatric case of hydrocephalus. Later in the 1920s, Dandy used cystoscopes for choroid plexus fulguration in the same patient group. Three years later, William Jason Mixter performed an endoscopic third ventriculostomy.[4,54-56] Almost 40 years later, Gerard Guiot explored the sella after an initial pituitary resection. This helped him to achieve minimal tissue trauma and better visualization with direct lighting and a close-up point of view.[57,58] In 1997, Carrau and Jho introduced the first purely endoscopic surgery to optimize surgery time and precision. They reported that four out of 50 patients underwent operation via sublabial-transseptal approach, using a rigid endoscope assisted with a microscope, the subsequent patients were performed through a nostril using only rigid endoscopes. Since then, there have been numerous improvements to endoscope techniques. For certain pathologies, these improvements have catalyzed a transition from microscopic to endoscopic surgeries.[59)]

There are still various limitations to endoscopic techniques. One of the most significant limitations is that the surgeon has no sense of depth because the image provided by the endoscope is projected onto a two-dimensional monitor. This deficit requires advanced training and experience before his proprioception adapts to viewing surgery in two dimensions.[58)] This may be the next revolution of neuroendoscopy. For instance, new binocular endoscopes and stereoscopic headsets may ameliorate this limitation. As neuroendoscopic surgery continues to improve and perioperative complications diminish, and hence, patient morbidities decrease and indications for endoscopic surgeries expand. One exceptional example is endoscopic pediatric neurosurgery, which has greatly benefited from this approach.[60-62)]

3. Moving toward 3D surgical experience

3.1 Enhancing the real world-virtual reality (VR) and AR

These realities produce interactive experiences with the real world and have improved the field of neurosurgery considerably. The main areas beneficiated by these tools are education, rehabilitation, spine surgery, and functional neurosurgery.[63,64)] Although there is evidence of VR applications in medicine since 1980 by the orthopedist Dr. Robert Mann, the first neurosurgical application of VR was in 2009 by Dr. David Clarke. He removed a left frontal meningioma using the neuroTouch simulator.[63)] Since then, more neurosurgical groups worldwide have included VR and AR in their practices.

In 1968, Ivan Sutherland and Robert Sprouli invented the first AR device that they called The Sword of Damocles.[65,66)] This invention led to image-guided neurosurgery, but it was not until 1985 that AR had the first neurosurgical application using an enhanced microscope that integrated 2D preoperative CT slices displayed monoscopically into the optics of a standard operating microscope. In 1995, an augmented stereomicroscope in the United Kingdom allowed for better depth perception and intraoperative registration accuracy from 2 to 3 mm projected to a multicolor display of segmented 3D cross-sectional imaging data that was passed directly into the microscope oculars as solid or wire mesh overlays.[67,68)]

In 1998, endovascular AR was applied by overlaying reconstructed preoperative vascular anatomy from CT or MR angiography onto a virtual screen displaying real-time X-ray fluoroscopy data, which load additional contrast required to generate angiographic roadmaps.[68)] In 2002, the first augmented neurosurgical endoscope for endonasal trans-sphenoidal approaches was developed, and volumetric 3D reconstructions of preoperative CT or MRI data were overlaid onto the endoscope video feed on an external display.[69,70)]

3.2 A learning experience-VR and AR in different neurosurgical fields

In neurosurgical education/training, several universities have introduced VR and AR to their microsurgical laboratories and operating rooms simulating challenging and stressful situations. These technologies have the advantage of being cost-effective for neurosurgical programs since digital models can recreate different surgical scenarios.[63)] Although these technologies might be replicated worldwide, the equipment needed to create a digital laboratory is expensive for most low-middle income countries (LMICs). This challenge has been identified by some groups of neurosurgeons focused on global neurosurgery and has created free/low-cost digital platforms available worldwide such as UpSurgeon and The Neurosurgical Atlas.[71)]

Another contribution to neurosurgical education was made by Gildenberg et al. who created a device that built a volumetric target from neuroimaging studies of a tumor by superimposing the volumetric target on a real-time video of the surgical field created by a stereotactic frame. The image would then be updated throughout the procedure to visualize only the part of the tumor under resection. Thus, the surgeon could guide the resection along the border of the lesion.[70)] Presently, this can be created with 360° composite images from cadaveric specimens, and the anatomy and surgical approach can be studied from almost anywhere via multiple available mobile applications.

In epileptic surgery, the correlation of preoperative cortical morphology with the intraoperative environment is of special importance. In 2011, Wang et al. created an AR approach based on manual landmark-based registration. An intensity-based perspective registration for camera position estimation demonstrated that the fusion method achieves a level of accuracy sufficient for the requirements of epilepsy surgery without any specialized display equipment.[72)]

Spine surgery is one of the fields that has been highly beneficiated by AR and VR. In 2013, Abe et al. introduced, in the spinal surgery field, an AR guidance system called virtual protractor to visualize a needle trajectory in three dimensions during percutaneous vertebroplasty. An augmented image was created by overlaying a preoperatively generated needle trajectory onto a marker detected on the patient. The accuracy of the system was evaluated by using a computer-generated simulation model in a spine phantom and five patients with vertebral fractures. The results were promising and showed that AR successfully assisted in vertebroplasty procedures, providing an ideal insertion point and needle trajectory.[73)] These technologies have complemented others such as surgical robotics or artificial intelligence and together have moved the field forward in terms of navigation, remote rehabilitation/surgery, patient education, and telementoring.[74)]

In 2014, Cabrilo et al. developed an AR system for aneurysm surgery that creates a virtual representation of skull anatomy, vascular anatomy, and aneurysms utilizing angio-MRI and angio-CT data. The system was used in the case of unruptured aneurysms. The images built were presented into the eyepiece of the microscope. This allowed for a continuous assessment and guidance during the surgery that resulted in a better outcome with less surgical exposure.[75)]

4. Epoch surgical technologies

Treatments in neurosurgery have been largely improved by technologies. The most significant neurosurgical subspecialties beneficiated by technological innovation are spine surgery, endovascular/cerebrovascular surgery, and functional neurosurgery.

4.1 Spine surgery

One of the early cervical internal fixations registered in history was done in 1891 by Hadra. He fixed the vertebras using a silver wire around the spinous processes in a figure-eight fashion. Dr. Foester following his work decided to fuse the atlantoaxial joint using fibular grafts.[76)] Despite those techniques having acceptable outcomes for the patients by that time, other spine approaches were tried for spine stabilization with nonfavorable results. However, in 1943, Dr. Tourney used facet screws to fuse the spine, and the results were significantly better than in the other techniques. He reported better outcomes for the patients, faster recoveries, and short periods of bracing, casting, and immobilization. Although this was the beginning of a new era for spine surgeons, surgeons learned that fixation did not replace the need for fusion and that arthrodesis remained the most important portion of the procedure. Hence, Briggs and Milligan complement this technique with posterior lumbar interbody placement.[76)] All these new screws and rods improved traumatic and degenerative spine surgeries, but they also improved the field of pediatric spine surgery, especially the use of steel rods attached to hooks in scoliosis to correct the alignments.[76,77)]

Another revolutionary moment in the history of spine surgery was minimally invasive spine surgery. This type of surgery emerged from the necessity of improving the outcome of the patients postoperatively. Hence, Hijikata, Kambin, and Gellman performed one of the first percutaneous nucleotomies, and some years later, in 1997, Yaşargil and Casper improved this technique using the microscope.[76,78,79)] These techniques continue evolving and combining technologies such as endoscopes, microendoscopes, and O-arms that have resulted in cost-benefit surgeries.

Nevertheless, the rapid growth of spinal instrumentation and lack of proper prospective and comparative studies led to a misuse of several spinal devices, especially pedicle screws, and different cervical arthroplasty plating devices. Surgeons and companies received multiple lawsuits due to poor outcomes and limited data regarding their efficacy.[76)] Consequently, in 2016, the US Food and Drug Administration reclassified the regulatory class of pedicle screws from Class III (general controls and premarket approval) to class II (general controls and special controls).[80)]

4.2 Endovascular and cerebrovascular surgery

Aneurysms and other cerebrovascular treatments have tremendously progressed after implementing innovative and creative technological devices such as coils, clips, and flow diverters. Vascular pathologies, especially cerebral aneurysms were treated via proximal ligation since 1700. After more than a century, in 1885, Victor Horsley treated a giant internal carotid artery aneurysm that touched the optic chiasm using bilateral cervical carotid artery ligation.[82)] This technique was modified by slowly and continuedly occlusion of the proximal blood vessel to the aneurysm over the course of days or weeks. The slow occlusion allowed the brain to adapt itself to the reduced blood flow until the flow was closed completely.

In 1911, Cushing created a silver clip while he was innovating new techniques and devices to reduce bleeding during tumor resection surgeries. This clip was placed during tumor resection and removed once the bleeding was controlled. The clip underwent some modifications by McKenzie and Walter Dandy who used it for clipping an aneurysm in 1936.[83)] Unquestionably, vascular clips created a new era for the treatment of aneurysms. As more aneurysms were treated using the clipping technique, different aneurysm shapes were identified and were not safely reachable using the standard silver clip. Thus, in 1969, Drake created the first fenestrated clip, and other vascular neurosurgeons such as Yaşargil, Sugita, and Spetzler kept modifying the size, shape, curvature, and metal material of the clips to make them more suitable for clipping aneurysms and compatible with MRIs.[82)]

As in other subspecialties, minimally invasive approaches have revolutionized surgeries and the field of cerebrovascular was not an exception. Endovascular surgery emerged as a surgical option for vascular pathologies when in 1980, Sundt treated basilar artery stenosis by performing a percutaneous transluminal angioplasty.[84)] Unfortunately, the procedure failed after a short period of time, and restenosis of the vessel occurred again. Thus, in 1996, Feldman et al. introduced stenting as a treatment option and showed it to be superior to angioplasty alone.[84)]

In the nineties, other groups treated intracranial aneurysms using platinum coil devices. These coils could be coated with a polymer or hydrophilic gels.[84)] Interestingly, morbidity was reduced significantly compared with open clipping surgeries. Other endovascular modifications emerged due to the variety of aneurysms shapes, especially for those aneurysms with wide necks. In this type of aneurysm, Moret et al. decided to use a balloon-assisted coiling technique in 56 patients, the results were favorable and the technique expanded worldwide.[85] Despite the positive impact of balloon-assisted coiling, some complex aneurysms required other intravascular device configurations to successfully close aneurysms. Hence, Higashida used the first stent-assisted coiling for a ruptured fusiform intracranial aneurysm from the distal vertebral artery and proximal third of the basilar artery.[86]

Other endovascular devices that revolutionized the field are flow diverters and most recently the intrasaccular flow disruptor as the woven endoluminal bridge. The uniqueness of these new devices is that they were designed considering fluid dynamics more than only the anatomy of aneurysms.[84] These devices have emerged aiming to treat successfully the most difficult and complex aneurysms with the benefits of minimally invasive surgery.

4.3 Functional neurosurgery

Electrical stimulation was one of the most iconic revolutionizing pivots in this field. Brain stimulation started with the implantation of electrodes in the caudate nucleus to treat a patient with depression and anorexia in 1948 by Lawrence Pool.[87] Subsequently, other psychiatric pathologies and pain disorders were the areas of study for brain stimulation. Since then, brain stimulation has evolved to treat pathologies that we did not imagine such as Alzheimer's disease, dystonia, epilepsy, aggressive disorders, and addiction.

One of the first diseases successfully treated was Parkinson's disease, by Sem-Jacobsen. His technique required identification of the target area using subcortical stimulation and then ablation of the area.[87] Although neural ablation might seem a risky technique, it is still used especially in LMICs because of the satisfactory results and affordable options.

Although electrical stimulation was preferred over neural ablation to treat different pathologies at different nuclei targets, the medical community was facing some logistic technical matters. Some of those challenges were that the battery of those brain stimulations was big to carry and did not last for a long time or the current frequencies were not high enough. Thus, companies designed different systems and batteries; some examples are the implantable pulse generator that allowed current frequencies of 130 up to 250 Hz, a closed-loop adaptive stimulation, or lithium batteries to last longer.[87]

The quality of life and functionality of these patients were significantly improved, and the field changed forever. To keep moving the field forward, researchers have analyzed the information generated by these devices; however, one of the limitations that have come up was the limited space to save the information generated in patients' own devices. Therefore, some groups created wireless, battery-free, MRI compatibility, and fully implantable neuromodulation devices that have already worked in different animal models and patients.[87,88] These modifications have allowed improvements in the research field and the outcome for the patients.

Another area of functional neurosurgery that has extraordinary progress due to the remarkable technological advance is the brain-machine interface. This area consists in translating the brain signals into an action using a computer/digital device that could be through electroencephalography, electrocorticography, or intracortical recordings. These signals can control neural prostheses that usually are cybernetic limbs connected to the patient's muscles. The application of this new field is not limited to motor diseases; it can also be used for epilepsy, attention-deficit/hyperactivity disorder, sleep disorders, etc.[89]

Future Directions

In the last 5 years, there has been a significantly increasing number of published studies about the impact of technologies in neurosurgery. These technologies are mainly virtual, augmented, and mixed realities in neurosurgery.[90] However, artificial intelligence and big data are also very powerful and revolutionary resources in neurosurgery.[91] The combination of VR/AR with artificial intelligence/big data would help us in identifying our surgical weaknesses, suggesting options to improve our skills and/or improving personalized approaches or treatments for our patients that ultimately would improve their outcomes.

Another important direction is global neurosurgery. Technologies such as telemedicine and teleradiology allow us to be in close communication with other colleagues and patients around the world. They also facilitate the exchange of knowledge and create collaborations that would close the gaps between low-to-middle- and high-income countries (HICs).

We consider it important to mention that these technologies do not replace human intelligence or human creativity; technologies help us in making our work more efficient, precise, and accurate for our patients.

Limitations

In most countries, technologies are part of our professional and academic daily activities. The lack of financial support for these technologies in LMICs creates a disparity in the field of neurosurgery. It is mandatory to seek options that would create a more homogeneous neurosurgical scenario worldwide.

Although most of the papers about technologies are published in HICs, LMICs have published very creative surgical techniques to perform contemporary surgeries. Some examples of those creative surgeries are the use of affordable and in-house material to perform minimally invasive surgeries. Apparently, this creative effort arises from the desire of moving the field forward despite the financial limitations.[92,93]

Conclusion

The future of different technologies focuses on developing technical improvements in speed of workflow, augmented optics for microscopes, increments in in-depth perception, and the creation of wearable devices to maintain focus during surgery and avoid eye fatigue. Novel enhancements are related to the interactions with virtual content, including the ability to freeze and manipulate virtual objects over a live real-world scene. Technologies are part of our daily activities and have positively impacted the field and outcome of our patients. Unfortunately, the latest technologies are not available worldwide, but we intend to spread the word and encourage people to innovate and/or apply some affordable technologies exposed in this review.

Author Contributions

Paul Castillo and Elizabeth Ogando-Rivas contributed equally to the research and preparation of this manuscript.

Conflicts of Interest Disclosure

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