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Application of Modern Neurosurgical Technologies in Low and Middle-Income Countries

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Abstract

In the last 10 years neurosurgical practice has seen exponential growth that has shattered all the imaginary borders of its predecessors. From tremendous advancements in neuroendovascular care to treat stroke patients that have sustained symptoms more than 24 hours ago, to minimally invasive robotic spine surgery that discharges patients' homes on the same day. All these advancements have drastically improved patient outcomes in the developed world. Many neurosurgical procedures have become more simplified and more intuitive thanks to computer software and hardware that guided neurosurgeons' decisions in treating patients operatively. However, while all these advancements have proven efficacy and efficiency in the operating room, these technologies are rarely applied or used in low-and-middle-income countries due to a lack of awareness or financial issues. There is the vast majority of newer technologies, that many low and middle-income country hospitals are simply not aware of due to limitations in general awareness or lack of educational materials backing up their efficacy.

Keywords: Neurosurgical technology; Virtual reality; Augmented reality; Neurosurgery in LMIC; Global neurosurgery.

Introduction

In the last 10 years, the merge of technology and healthcare has seen tremendous growth. From automatic craniotomy systems that prevent penetration of dura mater or elegant tissue of the brain, to robotic systems that help with pedicle screw placements and augmented reality that guides surgeons in safe tumor resections. All these advancements have significantly improved patient safety outcomes and more reliable approaches to the narrow neurosurgical corridors. Upon reviewing the current literature about technological advancements in surgical fields, many of them mention trials and successes in the developing or developed world. There are only a few published materials that widely discuss the application of these technologies in low and middle-income settings. We hypothesized that authors of many technologically advanced papers are simply overlooking the potential applicability and availability of these medical technologies there. However, the feasibility of the novel surgical technologies, especially in the LMIC (low and middle-income countries) regions might be a total success in achievement, since these geographical regions usually don't have the strict restrictions that many developed countries impose.

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Distance and feasibility

One of the successes of the application of advanced technology in LMIC settings was demonstrated by Tejas M Patel, Sanjay C Shah, and Samir B Pancholy In the paper "Long Distance Tele-Robotic-Assisted Percutaneous Coronary Intervention: A Report of First-in Human Experience" published on September 3, 2019 - Dr. Patel and his colleagues demonstrated tremendous success in treating cardiac patients remotely. While interventional cardiology and neurosurgery are different fields, endovascular access to many procedures is relevantly similar. Many neuroendovascular and cardio endovascular procedures access major vessels via femoral or radial arteries, therefore, allowing a comparison to neurosurgery directly. This exact scenario of remote neuroendovascular work might be the actual answer to bridging the gap between specialists in remote areas.

Availability and price

In another study, published by Sheth et al "Assessment of Brain Injury Using Portable, Low-Field Magnetic Resonance Imaging at the Bedside of Critically Ill Patients" we saw how portable MRI could be accessed on-demand in critical neuro patients. What piqued our interest in researching more about this machine is its uniqueness in mobility, price sensitivity, and accessibility of results on demand. These 3 elements are extremely important in underserved and rural areas of LMIC regions. One of the most devastating outcomes of the neurosurgery of LMIC is the unavailability of the right technology and specialists themselves. While our focus is not on the lack of specialists, but rather on technological feasibility and price points, it must be noted that the lack of specialist care is a huge burden and must be further investigated as well.

When we thoroughly assessed the paper by Sheth et al. it was clear how the portability of Hyperfine's MRI machine in 50 patients was a tremendous success in neurological Intensive Care Units (ICU) at Yale-New Haven Hospital in New Haven. The feasibility of rolling in the machine right at the bedside of a patient's head - is an ideal scenario for many underserved regions, as many hospitals are sometimes lacking a good interior foundation in the developing world.

Another very important concept of this modern technology is the price point of under $100,000 and the rapid availability of scanned results. This on-demand infrastructure of the hyperfine machine allows underserved and rural regions to get the right information on time, and potentially save a life of a critical neurosurgical patient.

Savings and the latest computer technology

While reviewing modern medical technologies, we couldn't mention augmented and virtual reality. Healthcare as a field essentially wants to be as organized and as safe as the aviation industry. The aviation industry implements numerous safety checks before deploying any protocols or scenarios, including the case-based Augmented Reality (AR) flight practice for pilots. Finally, the medical field started widely adopting the same scenarios for medical student education and surgical treatments. Neurosurgery particularly has been implementing numerous AR-based scenarios for resident-physician education, pre-and intra-operative scenarios, and more. Currently, the same Augmented Reality is utilized in modern operating rooms to visualize arteriovenous malformations (AVMs), tumors, and even the safe placement of pedicle screws in the spine. In the publication by Mascitelli J et al "Navigation-Linked Heads-Up Display in Intracranial Surgery: Early Experience," it described how heads-up display was utilized in 79 patients with 84 combined pathologies. The paper showcased how this technology helped neurosurgeons treat a very wide range of cranial pathologies safely during multiple stages of operation. This principle of safety and efficacy plus affordability might be the answer to many costly devices associated with neurosurgical operating rooms. While operating in tight surgical corridors such as the skull or spine, a neurosurgeon needs to know the position where he or she operates in. Therefore, neuronavigation constantly must be utilized in order not to damage the critical parts of the brain tissue. For the sake of this paper, it was very essential for us to find a solution that might be affordable and feasible in resource-limited settings. The augmented reality technology might be used exactly in this case, as was discussed in our previous published paper titled "Current and future use of virtual and augmented reality in neurosurgery: a literature review by Zhalmukhamedov, E., Urakov, T.M.

The adoption of technology and an open mind to try new things in surgical settings remains the challenge in many LMIC and developed countries. Therefore, we have a unique opportunity right now to showcase how these new technologies could majorly improve patient care and save money in resource-limited settings.

Methods

In this publication, we performed review research on highly effective neurosurgical technologies that have drastically improved neurosurgeons' experience in the operating room. The literature on the most significant technological advancements in neurosurgery and its application in low and-middle-income countries are reviewed and discussed. The applicability of technology ranged from the years of 2009 to 2022. Our findings showcased the average price spent on traditional imaging and interventional technology and compared it to the cost of acquiring the latest/new technological advancements. The availability and calculation of pricing were based on widely available price tags in scientific publications or original equipment manufacturers (OEM). The novelty of chosen technologies was based on scientific search queries from PubMed, Neurosurgical Meetings, and its proven applicability in the hospital settings of the developed world. Additionally, we surveyed 2 active neurosurgeons in the United States, who are pioneering the fields of spine augmented reality and advanced technology in endovascular neurosurgery.

To quantify the quality of this paper we narrowed down our search to the years 2009-2022. The criteria for inclusion of researched papers were based on novelty, applicability, feasibility, and active usage in surgical fields. The literature search conducted in March 2022 yielded in total of 303 results for "augmented reality in neurosurgery" and 448 results for "modern technology in neurosurgery". The sum of (n=751) search queries was screened. Out of these results, we narrowed down 70 papers that fit our criteria.

Since the socioeconomic status of the geographical region is also one of the central themes of this paper - a cost comparison was included as well. We collectively identified 30 available price tags from scientific papers and widely available prices on the

World Wide Web. Although our research focused on neurosurgery, a cross-disciplinary application of technology from medical specializations such as neurology, radiology, and surgery was included in this paper.

The era of robots and computer-powered technology

The days when neurosurgeons had to go to the dark radiology room to see the film scans of CT or MRI have been long gone from our lives in the developed world. Now many operating rooms are equipped with digital screens and the latest navigation systems to guide surgeons in the right region of the brain or spine. Not only does neurosurgery as a field embrace the technology, but it also pushed the boundary to improve operating techniques and patient outcomes. Many computer-related technological advancements have directly impacted the field of medicine at large. One of the most exciting things that many neurosurgeons embraced is virtual and augmented reality [1]. This haptic technology allows neurosurgeons to visualize patient-specific anatomy for preoperative and intraoperative care. One of the major adoptions in augmented reality is taking place in the skull base, followed by the spine and endovascular neurosurgery. In all three areas - a heads-up display is utilized to visualize the anatomy, pathological structures, and areas to avoid intraoperatively. The traditional microscope and navigation use - create an attention distractor for the surgeon while operating in the tight corridors of the surgical exposure. However, the use of a heads-up display mounted on the head or glasses of the surgeon - allows distractions flow of surgery and is less prone to errors [2]. This technology was a tremendous help and improvement in the workflow of the operator, from planning a skin incision, craniotomy, tissue differentiation, etc. More than 84 cranial-based pathologies such as aneurysms, Arteriovenous Malformations (AVMs), meningiomas, osteoblastoma, Cerebrospinal Fluid (CSF) leaks, and more are accurately addressed with the help of this technology (figure 1) [2-4]. The application and benefits of spine surgery could be observed in figure 2, where T. Urakov MD from the University of Miami utilizes augmented reality for pedicle screw placements.

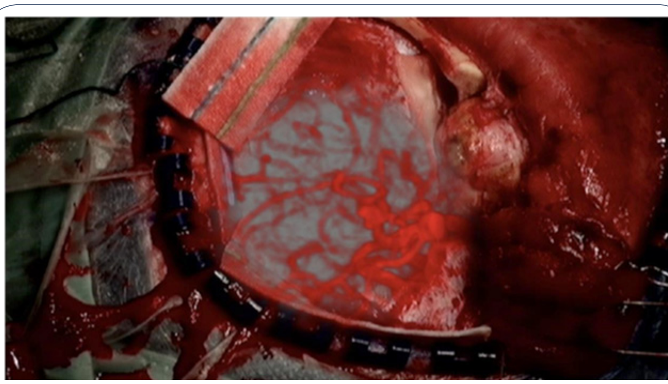

Figure 1: Example of The Intraoperative Brain Imaging System (Ibis) navigation.

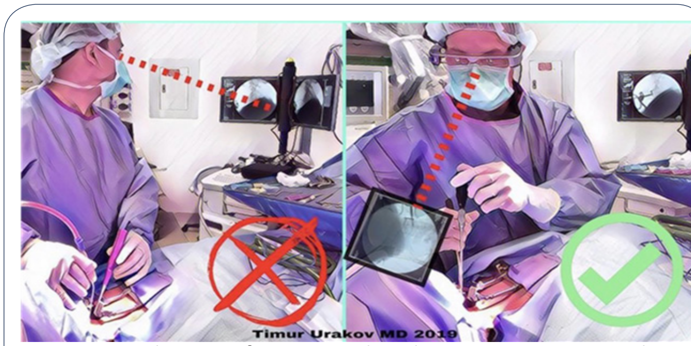

Figure 2: Application of Augmented Reality in spine surgery without losing focus on the operating site.

When it comes to robotics, spine and endovascular fields have shown massive progress, especially in the United States and Europe, among which the Mazor and Rosa family robots were prevalent the most in spine cases [4]. Even though according to the survey of neurosurgeons practicing in the global regions, it was stated as a positive surgical outcome for the patients, the cost of acquiring and maintaining this technology has proven significantly high [5].

In an example of the spine, endovascular and cerebrovascular fields - a remote video robot, robotic-assisted angiography, guided microscopes, clipping, and coil insertion devices have been pioneered in this arena [6]. The successful treatments of saccular sidewall aneurysms of the basilar artery and carotid artery angioplasty were successfully treated by utilizing CorPath GRX Vascular Robotic System in Toronto and Philadelphia University hospitals [7,8]. Another significant breakthrough in the endovascular and cerebrovascular field was telemedicine application, especially in the areas where stroke unit teams are scarce or non-existent. The significant time management in TPA administration of Cerebrovascular Accident (CVA) patients and door-to needle times for endovascular procedures were significantly reduced - thanks to Telestroke systems. The current tele-stroke application improved the treatment rate from 19% to 78% in Southeast Bavaria, Germany [9]. These are so far the most successfully diverse cases reported in neurosurgery around the world.

While technology greatly contributed to the advancement of neurosurgical care intraoperatively; perioperative care technologies remain the golden standard for identifying pathological lesions in the central or peripheral nervous systems. Particularly CT and MRI machines are still one of the oldest and most reliable methods to identify pathology promptly. While these machines remain bulk and financially significant for the hospitals, there were some advancements in this area. In 2020 one of the pioneers of portable MRI machines was born, Hyperfine Research inc. received full clearance for the usage of the first fully functional portable MRI. This machine has significant advantages for patient care and financial incentives [10]. The machine provides significant mobility within the patient's location due to its size and it costs around $50,000 in comparison to the traditional high-field MRI machine which costs from $1 to USD 3 million.

The next significant step in a potential application in neurosurgery is Metaverse. According to a broad definition, a Metaverse is a 3D virtual reality world powered by real users' input and interaction. Generally speaking, it's a virtual world where people can socialize and actively participate in various activities, including work, education, play, and general participation for leisure time [11]. Dr. Koo from Seoul National University, Bonding Hospital, Korea - performed one of the first educational lung cancer surgery through Metaverse. Essentially, this operating room had significant investments to become "smart" also known as a technologically savvy operating room. The operating room was equipped with 360-8K-3D cameras and XR immersive sound system for seamless surround sound. All participants had an option either to have a 3D headset (figure 3) for a more immersive experience or simply a computer screen to attend this surgery LIVE. As a main theme of Metaverse, each participant was asked to create an avatar or gamified persona to enter the metaverse hall where the surgery was broadcasted. With the help of 3D cameras and smart technologies in the operating room, each participant was able to observe surgery virtually from any corner. This exact application of Metaverse has significant advantages over in-person surgery attendance. Many academic surgeons who actively teach medical students, residents, and fellows – understand that overcrowding and low visibility of the operating field is a huge issues for in-training doctors. As neurosurgery requires a delicate technique in executing various procedures, observation of an operating physician's hand movements is critical for proper education. Additionally, some ergonomics of an operating room could be observed as well, it helps physicians-in-training understand the role of each person in the operating room and how they strategically move around [12]. This exact technology might have a significant improvement in operating techniques for surgeons who work in remote locations or lack knowledge in advanced neurosurgical procedures. Another positive outcome of utilizing Metaverse's virtual reality is COVID-19 precautions in crowded places. Metaverse could be deployed anywhere in the world, which allows participants to be in their comfort zone and eliminate the social distancing concerns while observing surgery LIVE. In addition to the metaverse, there are some exciting developments in haptic technology, such as Meta's haptic feedback glove that allows participants to feel the object, which is essential for any surgeon's experience [13]. However, haptic technology remains in the developmental phase of Metaverse or Augmented/Virtual Reality for surgery and the public at large.

Figure 3: Example of 3D headset and joystick.

Current challenges of low-and middle income countries

Critical imaging

While modern technology continues to improve, some traditional modalities of obtaining critical neuroimaging are still lacking in LMICs. One of the main resource limitations in LMIC is Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). These two critical machines that help identify critical intracranial pathologies such as bleeding or hematomas in emergency settings, significantly reduce morbidity and mortality in the mentioned above geographical areas. A survey conducted from 2015 to 2016 in Sub-Saharan Africa revealed a sum of 84 MRI machines for a population of 372, 551, 411 people [14]. These statistics are very disappointing, knowing the high significance of motor vehicle-related accidents due to poor road Infrastructure in the LMICs [15,16].

Lack of specialists in the field

Many rural and resource-limited geographical locations of healthcare systems usually lack many specialized surgeons. This lack of specialist surgeons is especially felt in the neurological surgery arena [17]. There are significant barriers such as lack of training in the reachable area for physicians to specialize, inadequately trained operative personnel, and lack of equipment.

Additionally, it's worth noting that neurosurgery is considered one of the most expensive specialties to train in. The average cost to train a fully competent neurosurgeon in the United States is approximately $341,978.00 plus $27,876.36 for annual expenses [18]. This amount is truly astronomical for the developing and LMIC regions, as spending per physician education in Colombia for example, costs $80,971.80 for a privately held university and $54,971.79 for a public educational institution [19].

One can see the huge gap in spending on physician education, therefore many LMIC doctors are unfortunately at a big disadvantage for specialized education [20]. While neurosurgery is considered one of the technically and academically challenging specialties, not many countries can afford nor have the luxury to train one. One of these LMICs are Caribbean islands, in St. Lucia for example, there are only 2 neurosurgeons who take care of a population of 180,287 people [21]. This proportion seems extremely unreasonable and impossible at the same time, to address urgent neurosurgical procedures that can save a life. It's worth noticing, that both neurosurgeons on this island have received their neurosurgical education overseas to help locals address their neurosurgical challenges.

Even though neurosurgery is one of the most expensive specialties out there, one of the scientific studies proved to have an economic benefit to the country. Hubbard et al. calculated Disability Adjusted Life Years (DALY) per neurosurgical intervention in Haiti. The total benefit to the country's economy due to neurosurgical interventions was from $2.5 to $5.5 million [22]. These significant numbers, upon proper presentation, could pave the way for the funding of neurosurgical care and education in LMICs.

The potential technology that could be applied to LMICs

Earlier in this paper, we discussed some of the latest technological advancements in neurosurgery and how they benefit patients. While many of these technologies will require a substantial investment, some options could be affordable for many LMICs. In table 1 we present an example of a comparison between traditional cost versus investment in the latest imaging technology. The average cost of traditional technologies was calculated based on the popularity of the products within hospital systems in the developed world. Malham et al. provided an excellent overview of major pricing points, which guided us in calculating the average price point in table 1 [23]. The prices provided in table 1 have been closely approximated, as fluctuations of the exact prices could be changed by manufacturers or distributors daily. We calculated the difference between traditional technology and modern technology and captured total savings.

The following price range models were identified:

1. Fluoroscopy imaging: $250,000 - $500,000
2. Intraoperative CT: $600,000 – $1.2 million
3. Neuronavigation system: $250,000 - $700,000
4. MRI Scanners: $200,000 - $3 million
5. AR Navigation System (P.e HoloLens 2) + a set of 4 digital cameras: $7,000 - $10,000

The cost of a portable Hyperfine MRI unit and complete AR System with needed cameras for augmentation & 3D imaging - was based on the original equipment manufacturer's (OEM) price and a widely available price tag on the internet.

Table 1: Imaging technology cost comparison for traditional vs. new technology.

	MRI Machine		Neuronavigtion	
Total Savings	Average Traditional Cost	Hyperfine Portable MRI Cost	AR Navigation System Cost	Traditional Neuronavigation Cost
	≈ $1 million	≈ $50,000	≈ $10,000	≈ $483,000
	$950,000		$473,000	

Another critical point of price sensitivity is associated with maintaining the actual equipment. The cost of maintenance of traditional MRI and Neuronavigation is very significant and should be considered thoroughly. The average cost of repairing a traditional imaging system is between 4 to 14 percent of the actual acquisition cost [24]; additionally, there should be personnel that is adequately trained in repairing these machines. All these costs should be adequately calculated and/or negotiated before the final acquisition. The newer systems on another hand might be more complex in terms of technological hardware, however, the maintenance cost is significantly lower in comparison to traditional systems.

While considering a wide range of neurosurgical procedures for this research, we narrowed it down to only essential neurosurgical procedures that are critical for a patient's survival and quality of life. Therefore, for the quality of this paper, we are considering critical care/trauma neurosurgery, spine, and endovascular neurosurgery. Upon reviewing multiple published papers, these exact fields of neurosurgery are tended to be frequent in terms of the scope of LMIC cases [25]. However, the largest contributor to neurological diseases in terms of DALY is found to be a cerebrovascular accident (CVA). If we look at Nigeria as an example of a developing world, the highest mean direct cost of stroke was $8424 USD [26], while the highest average annual salary in the country was $1243.56. Even though Nigeria as a country participates in Universal Healthcare Coverage (UNC) the difference of $7180.44 per single stroke accident is a significant amount for the country and patients alike. Additionally, the quality of treatment is not always guaranteed, as the scarcity of neurosurgeons in Nigeria is massive 97 neurosurgeons for a population of 200 million [27]. This statistic doesn't even include super-specialized training in the field.

Therefore, we propose an investment in telerobotic and robotic endovascular robots, that could be operated either remotely or in the hospitals themselves. While endovascular robots are still in the pre-approval stages, it has already shown some great potential to change stroke treatment forever, especially in remote areas.

The first-ever long-distance remote endovascular procedure was successfully implemented in India. The group of intervention cardiologists successfully deployed CorPath GRX®, (Corindus Vascular Robotics, USA) at a 32 km distance between operating medical centers. What was essential for this procedure is the availability of a catheterization staff and unit, an obvious technology of the CorPath robot, and reliable connectivity infrastructure [28]. Even though this Indian success has proven a breakthrough success, there are still more investigations and trials that need to be deployed to prove the efficacy worldwide. The success of Patel et.al has proven, that rural medicine might finally bridge the gap of specialist doctor shortages in rural areas.

However, telerobotic interventions, on the other hand, are already actively utilized in remote areas of the developed world and have proven a better outcome in those regions [29]. These robots will help local non-specialized neurosurgeons receive guidance from physicians who are specifically trained in this area in the developing or developed world. The average cost to implement a telestroke unit in a hospital is $46,000 [30]. Even though, this seems like a large investment especially for LMIC regions, the long-term benefit outweighs the burden of investment, as we showcased in an example of Nigeria's DALY. As everyone knows that time is of the essence, especially in the stroke scenario, therefore, it's important to provide a needed or guided intervention on time. The therapeutic window for the application of thrombolytic therapy or immediate lifesaving neurosurgical intervention could be drastically decreased, once a telestroke unit is operational. While investing in this telerobot might be a big one-time cost, the total burden of CVA outcomes in LMIC might be easier financially on the government. For the reference of the reader, we provided a visual cost representation of the cerebrovascular robot and telerobot in table 2.

Table 2: Representation of prices for robotic technology in vascular neurology/neurosurgery.

Average cost of Telerobot	Average cost of CorPath GRX Robot
≈ $46,000	≈ $650,000 [31]

Results

In this paper, we demonstrated how the latest technological advancements in neurosurgery could play a vital role in the improvement of patient care in LMICs. Our findings have shown how the latest imaging technology of portable MRI, AR Neuronavigation, Telerobot, and Endovascular Robots have a tremendous advancement in improving care and could save money for local government and healthcare systems. The comparison of acquiring new technology versus the cost of traditional treatment has shown favorable towards technology. An investment in modern technology will allow any LMIC region to become more progressive in its approach to healthcare needs, especially in times of the COVID-19 pandemic.

The significant cost reduction of DALYs spending due to the implementation of technology, will further improve not only the population's health but also economic output, and bring up healthier nations.

Conclusion

The advantages of modern technology in the neurosurgical specialty play a vital role in patient survival. Technology that has proven a positive outcome for neurosurgical patients, must be seriously considered for implementation in LMIC hospital systems. The only logical setback of the mentioned technologies - is the financial upfront cost to the facility or government. However, the evidence provided on the financial benefits of long-term outcomes might be a win-win situation for providers and policymakers alike. This literature review research should provide a foundational groundwork for an open dialogue within LMIC regions to adapt the novel technological advancements in neurosurgery. Further investigation and feasibility of the proposed technology must be carried out to solidify a purchase decision per country of origin and their needs.

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