New frontiers in intraoperative neurophysiologic monitoring: a narrative review

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Background and Objective: Neurological insults during surgery arise from anatomic and/or physiologic perturbations. Intraoperative neurophysiologic monitoring (IONM) fills a critical role of ensuring that any neurological insults during certain surgical procedures are caught in real-time to prevent patient harm. IONM provides immediate feedback to the surgeon and anesthesiologist about the need for an intervention to prevent a neurologic deficit postoperatively. As important as it seems to have IONM available to any patient having surgery where a neurological injury is possible, the truth is that IONM is unavailable to large swaths of people around the world. This review is intended to bring attention to all of the ways IONM is critically important for a variety of surgeries and highlight the barriers preventing most patients around the world from benefiting from the technology. Expansion of IONM to benefit patients from all over the world is the new frontier.

Methods: We searched all English language original papers and reviews using Embase and MEDLINE/PubMed databases published from 1995 to 2022. Different combinations of the following search terms were used: intraoperative neuromonitoring, neurosurgery, low-income countries, cost, safety, and efficacy.

Key Content and Findings: We describe common IONM modalities used during surgery as well as explore barriers to implementation of IONM in resource-limited regions. Additionally, we describe ongoing efforts to establish IONM capabilities in new locations around the world.

Conclusions: In this paper, we performed a review of the literature on IONM with an emphasis on the basic understanding of clinical applications and the barriers for expansion into resource-limited settings. Finally, we provide our interpretation of "new frontiers" in IONM quite literally facilitating access to the tools and education so a hospital in Sub-Saharan Africa can incorporate IONM for their high-risk surgeries.

Keywords: Intraoperative neurophysiologic monitoring (IONM); neuromonitoring; low-middle income; countries; patient safety barriers

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Introduction

Across a multitude of surgical procedures, inadvertent injury to the nervous system and its structures is a real possibility. The severity of injury depends on both location and type of insult, and unless the nervous system is monitored in real-time, the injury is likely to go unnoticed during the procedure (1-4). New postoperative neurologic deficits may include loss of sensation or muscle strength as well as cognitive changes, depending on where the injury occurred. No matter the end result, it is imperative to provide patients with safe surgical conditions and to prevent inadvertent harm. Intraoperative neurophysiologic monitoring (IONM) was introduced in the 1970's in an effort to reduce perioperative neurologic deficits (5). Over the intervening decades, numerous technological advancements allowed the field of IONM to be able to test the functional integrity of various parts of the nervous system with high sensitivity. In essence, IONM aims to increase patient safety and prevent neurologic injury intraoperatively. The role of IONM in surgical procedures remains controversial largely due to the lack of prospective randomized controlled trials demonstrating neurologic outcome benefits over patients who do not receive IONM, with the exception of recurrent laryngeal nerve monitoring for thyroid surgery (6). Of note, these types of trials are often not performed due to ethical limitations, thus we are left with case series, cohort studies, and retrospective studies for evidence on the utility of IONM (7).

In the Unites States and other high-income countries, IONM utilization is increasing. Resource-limited countries, however, continue to be unable to provide patients with the same level of care, particularly when surgical interventions can injure the nervous system. Neurologic outcomes in a variety of spine surgery types are improved when IONM is used. For example, in complex spine surgery, such as scoliosis correction, IONM has long proved to guide surgical planning and prevent neurologic injury (7). Outside of high-income countries, literature on IONM is largely non-existent. One recent study of IONM use during cervical and thoracic spine surgery in a lower-middle-income country (LMIC), showed IONM had a profound impact on patient care (8). Here, the clearest benefit of IONM proved to be in dissection of intramedullary spinal cord tumors. Surgeons were able to safely guide their resections according to IONM responses so as to minimize patient harm.

This review focuses on the current traditional applications of IONM and examines the expanding role of IONM globally in both high-income countries as well as LMICs. Reasons for the propagation of IONM use in resource-rich areas are discussed, including meeting the perceived standard of care and improving patient outcomes. Additionally, we carefully examine limitations and barriers to widespread use of IONM, particularly in LMICs. Lastly, we highlight our ongoing efforts to spread IONM use through education and training, both in the United States and abroad. We present this article in accordance with the Narrative Review reporting checklist (available at https://atm.amegroups.com/article/view/10.21037/atm-22-4586/rc).

Methods

A bibliographic search of the databases—Embase and MEDLINE/PubMed was performed using a combination of relevant keywords and subject heading terms for intraoperative neurophysiological monitoring, neuromonitoring, low-middle income countries, and patient safety barriers. Most of the search formulas we used are shown in *Table 1*. The results were further curated by authors based on English language, year of publication, citation count, study type, and was then used to serve as reference material for this review. Secondary searching included manual searching of relevant reference lists for articles not identified in the primary search and review of citation listings.

Traditional IONM applications

Spine surgery

Surgeries of the vertebral column and spinal cord have increased significantly in recent decades with approximately 80 per 100,000 people undergoing elective spinal fusion surgery annually (9). Surgeries of the spine are the most common procedures where IONM services are employed (10). Although no standard of care exists on which cases require IONM, the cases most commonly associated with its use include: vertebral trauma, anterior cervical discectomy and fusion (ACDF) with myelopathy, posterior cervical fusion, spinal deformity, and spinal cord tumors (11-13). In the United States, the increased use of IONM is mostly attributable to a massive increase in spine operations. From 2008 to 2014 alone, there was nearly a three hundred percent increase in the number of cases (14). Urban teaching hospitals and large academic centers are

Table 1 Summary of search strategy

Items	Description
Date of search	July 30th 2022
Database	EmBase and MEDLINE/PubMed
Search terms used	Neuromonitoring, neurosurgery, neuromonitoring in low-income countries, neurosurgery in low-income countries, intraoperative neuromonitoring safety, intraoperative neuromonitoring efficacy, intraoperative neuromonitoring cost, intraoperative neuromonitoring effectiveness, intraoperative neuromonitoring outcomes
Timeframe	1995–2022
Inclusion criteria	The main focus of the search was directed to find literature written in or translated into English relating to the implementation of neuromonitoring
Selection process	Literature search was independently conducted by all authors

by far the highest utilizers of IONM, while non-teaching or community-based hospitals lag significantly behind and rural centers rarely utilize this resource (15).

Indeed, spine surgery was the catalyst for the introduction of IONM once more aggressive approaches to spinal deformities were introduced in the 1960's and 1970's (16). The resultant increase in the rate of neurologic complications led to the development of different approaches to ensure the integrity of the nervous system. The first method, the Stagnara wake-up test, involved asking the patient to perform motor and sensory functions while under a lightened plane of anesthesia during surgery (5). Although arguably the most accurate method, and still done in certain instances today, there are significant limitations. First, this test cannot be performed continuously throughout the surgery. Rather, it is performed in an intermittent fashion at specific milestones of the procedure and as a result critical injuries can arise between tests (17). Second, a host of logistical challenges to the anesthesia team and the patient exist. For the anesthesia team, titrating the anesthetic to allow for patient comfort and cooperation is not trivial. In some instances, no amount of anesthetic tinkering can provide the needed conditions for accurate neurological assessment while ensuring patient comfort and safety (18,19). Many patients prefer to be unconscious for the duration of surgery and are unwilling to be subject to the trauma of being awake on the operating room table, intubated, and prone. For these reasons, today's practice utilizes IONM almost exclusively (17).

The goal of IONM in spine surgery is to monitor the integrity of the spinal cord and spinal roots during surgery in real time to allow the surgical and anesthesia teams opportunities to correct insults or injuries before becoming permanent (20). Initially, somatosensory evoked potentials (SSEPs) and electromyography (EMG) were the only modalities used during spine surgery, however, false-negatives proved frequent (21,22). In these instances, patients awoke with neurologic deficits despite unchanged SSEPs and a lack of spontaneous EMG activity throughout the case (5). The introduction of motor evoked potential (MEP) monitoring in the 1980's led to a decrease in false-negatives, meaning more detrimental neurologic insults were captured while the procedure was in progress (21). The combination of SSEP and MEP allowed for monitoring both the integrity of anterior motor function as well as posterior sensory function of the spinal cord (23). IONM has since been shown in multiple studies to decrease the rate of neurologic complications across a multitude of spine surgery techniques in a heterogeneous population (24-29). Some studies, demonstrate no benefit to the use of IONM in uncomplicated, minor spine surgery including single level spine surgery and ACDF procedures (30,31).

Unsurprisingly, the risk of neurologic injury increases with the degree of correction and thus IONM proves more useful during major spine surgery involving the spinal cord, infections, or major spinal column anatomic corrections (32-34). Evidence from Nuwer et al. shows a 50% decrease in complication rate when an experienced team of IONM, surgery and anesthesia worked together demonstrating the benefit of a consistent and familiar approach (35).

During surgeries involving the spinal cord, which are considered from the occiput to the second lumbar vertebral body (L2), it is beneficial to use SSEP, MEP and EMG modalities to maximize the sensitivity and specificity of neurologic insult detection (36-38). Below L2, MEPs are seldom used as inadvertent compression or injury to the spinal cord is less likely, although this may no longer be supported by current literature in patients with known spinal stenosis at other levels (39). Additionally, since spinal roots exiting at L2 and below carry both sensory and motor fibers, MEP could be beneficial for more complete monitoring of peripheral nerve function (40). Monitoring of SSEP and MEP modalities from the upper and lower limbs in every case, regardless of the direct involvement of those spinal levels, helps determine global versus local neurologic insults in the event of a signal change (41). SSEP signals are particularly helpful in localizing injuries because the responses are recorded at multiple anatomic locations along the transmission pathway including brainstem and cortex as this signal ascends the sensory pathway. During posterior spine surgery, brachial plexus injuries due to improper positioning or in patients with at risk peripheral nerves can also be detected with the use of the SSEP modality (42). During anterior cervical spine procedures, it is common to monitor function of the recurrent laryngeal nerves (RLN), the specifics of which will be discussed in the next section (43). Lastly, thoracic EMG monitoring is typically omitted with procedures involving the thoracic spine as the muscles innervated at these levels are difficult to monitor and interpret, not to mention the fact that neurologic injury is associated with relatively mild morbidity (44).

Neck surgery

Surgical interventions involving the neck are most often related to thyroid and parathyroid removal, but also include other tumor removals and neck dissections. Carotid artery procedures are covered more extensively in the vascular surgery section. Pertinent nerves in the neck include the vagus nerve with its RLN branches and the spinal accessory nerves. The goal of IONM in these procedures is primarily surgical identification of neural structures through intermittent, direct stimulation (45). Accurate identification aids surgical decision making in real time and verifies intact neural pathways at the conclusion of the procedure. Moreover, continuous monitoring of spontaneous EMG activity in the muscles innervated by these nerves provides the surgeon with information about the function of the nerve during surgical manipulation. Traction, retraction, cautery and dissection near the nerve can elicit spontaneous muscle activity that is important for the surgeon to recognize (45).

Recording the EMG activity elicited by intentional surgical stimulation of the RLN is possible utilizing a specialized endotracheal tube (ETT) with integrated electrodes that must be in contact with the vocal folds (46). In these procedures, proper positioning of the ETT is critical and placement with a video laryngoscope led to improved detection of successful surgical stimulation at our institution. Despite proper ETT placement at the time of airway instrumentation, patient positioning and intraoperative ETT movement can result in loss of contact between the electrodes and the vocal folds, can lead to the inability to record stimulated responses. Similarly, to spine surgery, procedures deemed high risk for neural injury, IONM can decrease the rate of neurologic injury leading to vocal cord dysfunction (47).

Intracranial surgery

For decades, neurosurgeons have used IONM during intracranial surgery depending on the type of surgery, location of pathology, and resource availability. Intracranial surgeries provide the rare opportunity to utilize nearly every modality available: MEP, SSEP, brainstem auditory evoked potentials (BAEP), continuous and triggered EMG, and electroencephalography (EEG). No consensus exists for modality selection, yet given the highly sensitive nature of brain anatomy, a broadly conservative approach is generally undertaken (48,49). During brainstem surgery, for example, BAEP, cranial nerve EMG as well as MEP and SSEP modalities provide a wide array of information relevant to all the surrounding neural structures and pathways. In these surgeries, both surgical localization of neuronal tissue as well as monitoring of adequate perfusion during retraction is critical. For cortical surgery, MEPs and SSEPs are used to locate primary motor and sensory cortex areas when anatomy may be distorted as in cases of large tumors (50,51). In instances of cortical surgery near eloquent areas, electrocorticography, in conjunction with various stimulation paradigms, are used to enable the neurosurgeon to map out functional versus nonfunctional tissue via direct electrical cortical stimulation (52). As a consequence of direct cortical stimulation, seizure activity may arise, thus continuous monitoring is recommended and epileptiform discharges must be dealt with promptly when present (53). Cessation of electrical stimulation is paramount and steps to terminate the seizure activity are instituted.

Vascular and neuro-vascular surgery

Certain procedures on the vascular system can result in catastrophic neurologic insults. For example, carotid artery procedures can result in a large stroke while aortic artery procedures can result in paraplegia (54). Thus, there is increasing interest in utilizing IONM to monitor for compromise of neurologic structures perfused by the target vessel or vessels, as well as to reduce the risk of neurologic deficits after these types of surgeries (55). Carotid surgeries commonly employ SSEP and continuous EEG to monitor the brain (56). These modalities serve to provide the surgeon with information about collateral blood flow to the brain once the affected carotid is clamped. Any notable changes associated with test clamping can lead the surgeon to place a shunt or to have the patient's blood pressure increased in blood pressure (57,58). In surgery involving the aortic arch, circulatory arrest may be needed. Here, blood flow to the brain ceases for the duration of the repair putting the brain at risk of global ischemia and infarction. During this critical time period, the cerebral metabolic rate for oxygen is minimized through significant hypothermia and pharmacologically induced quiescence of electrical brain activity (59). Prior to initiation of circulatory arrest, the surgeon verifies that the continuous EEG is isoelectric, which is maintained throughout arrest. Once the patient is rewarmed and closing begins, EEG and SSEP are monitored to ensure a return to baseline values as well as to verify symmetric responses. Any abnormalities in returning EEG patterns or SSEP waveforms following reperfusion could be indicative of stroke. Surgery of the descending thoracic aorta benefits from IONM because the thoracic aorta provides substantial blood flow to the anterior spinal cord, where motor neurons sensitive to ischemia reside. Adequate blood flow to the spinal cord must be ensured during all stages of surgical repair (60).

Other types of vascular surgery that often use IONM include spine tumor embolization, cerebral artery aneurysm clippings, and removal of dural arteriovenous fistulas and arteriovenous malformations. Some spine tumors are highly vascularized and surgical removal may lead to a large intraoperative blood loss during resection. To mitigate blood loss, surgeons can assess the vascularity of the tumor with angiography and in cases of high vascularity, choose to selectively embolize its blood supply. Embolization carries risk of inadvertent interruption of blood supply to the spinal cord. MEP and SSEP modalities are used in these instances and monitor for changes with administration of local anesthetics or barbiturates as a precursor to embolization (61). If changes are observed, the area is not embolized as there is insufficient collateral blood flow to prevent a neurologic injury (62). Cerebrovascular surgery can also benefit from IONM, particularly from the SSEP and EEG modalities. The effectiveness of neuromonitoring here is largely dependent the location of the abnormality and its complexity. Many neurosurgeons forego IONM for cerebral aneurysm coiling or stenting because of the use of real-time angiography (63). However, in surgical clipping procedures, IONM plays a role in monitoring for compromised blood flow from either the temporary or the permanent clips (63).

Barriers to IONM utilization in resource-limited areas

The inherent risk placed on neural structures during specialized procedures necessitates a method by which surgical teams can mitigate injury. Over the preceding decades, surgeons in high-income countries have vastly increased their utilization of IONM with the goal of decreasing neurologic injury and therefore improving patient outcomes (15). Widespread adoption of IONM has occurred in the developed world, yet distinct limitations have, to date, prevented its incorporation in resource-limited settings. While no prospective, randomized clinical trials exist, and will likely never exist given the current medicolegal environment, available data both supports and discourages its use (64). However, these same authors state that the preponderance of the evidence supports the routine use of IONM for a diverse array of surgical procedures and additionally support increasing technological and supervisory capacity to implement this technology in locations where it does not currently exist (11,12).

LMICs face unique and often unprecedented challenges when attempting to incorporate IONM into neurosurgical procedures to guide clinical decision making. Some of these challenges are related to availability of resources, both material and personnel, power grid suitability and electricity grounding issues, staff familiarity and comfort with the technology, and finally cost.

Despite ongoing efforts, building access to neurosurgical care in LMICs has proven difficult and with the growing need for adequate neurosurgical care, the same can be said about access to Certification for Neurophysiological Intraoperative Monitoring (CNIM) technologists and interpreters (65,66). According to a recent inquiry made to the ABRET database, there are approximately four thousand technologists in the United States, 121 technologists outside of the United States with only 6 individuals for the entire continent of Africa. While this database is unable to capture all qualified technologists outside of the United States, it does illustrate that comparable education and training outside of the United States is uncommon. Additionally, individuals with the training to interpret IONM are even more scarce worldwide. This is likely due to an inexorable cycle where a lack of personnel leads to a lack of utilizing IONM which in turn leads to limited opportunities for individuals to train and implement their skill set. Training a CNIM can be expensive and time consuming though necessary to provide safe and effective patient care. In order to become a CNIM through ABRET, individuals must undertake rigorous didactic training, log 100–150 cases and pass a certification exam. Without a clear path to a stable practice, it is reasonable that individuals would choose not to undertake such training. Access to monitoring equipment is limited and can also be cost-prohibitive, electrodes and appropriate anesthetic drugs that don't interfere with IONM can also add to the overall cost burden.

In order for any technology to be successfully implemented in the operating room, all staff should have a degree of comfort and familiarity with said technology. In the case of IONM, it is imperative that surgeons, anesthesiologists, technologists and interpreters have a facile understanding of IONM and its implications to the procedure in order to use the data gathered to make fast and appropriate clinical decisions during a surgery (1). The addition of IONM to a surgical procedure necessitates changes to the culture of the operating room including extending planned surgical times, anesthetic management and surgical interventions.

Publications on the experience with *de novo* implementation of IONM programs around the world is scarce. There are some success stories including a recent case series published from Cairo University in Egypt where IONM was implemented for spine and intracranial surgeries (8). At this institution, IONM was readily adopted and continues to gain popularity. IONM was used to guide maximal to subtotal tumor resections based on cortical mapping and recoverability of motor and sensory signals. The surgeons noted that in several cases it allowed them stop or reverse surgical manipulation and alert the anesthesiologist to increase perfusion pressures or alter the patient's temperature. In the retrospective analysis of their patient cohort, they found that patients who had irreversible MEP alerts, using a 50% reduction in amplitude as the cut off, were likely to have postoperative deficits. Some of the challenges they noted included a defect in electrical grounding, limited availability of drugs like succinylcholine and sugammadex, and limited experience of the anesthesiologists with managing total intravenous anesthetics without processed EEG monitoring for depth of anesthesia. On a practical level they noted that there was significant electrical interference with the acquisition of signals during their initial cases which lead to inadequate monitoring. This led to an investigation of their facilities and ultimately repair of electrical grounding. It is common for operating room equipment to "leak" electricity which can interfere with IONM signals. Older facilities and equipment are more likely to have this problem.

Despite the known benefits of IONM for neurosurgical procedures in preventing iatrogenic injuries resulting in permanent and debilitating harm, cost continues to be prohibitive for its widespread adoption (12,67). In a survey performed in higher-middle resource countries in Latin America it was found that although 68% of the spine surgeons surveyed believed IONM was vital for complex spine surgeries, the cost barrier limited its use to only 57% of cases (68). Such data is not readily available for LIMC but one can imagine that cost is an issue as well and potentially even more limiting.

Education to expand IONM globally

At our institution, our team of neuroanesthesiologists not only provide anesthesia care for neurosurgical and complex spine patients, but also interpret IONM.

Having an integrated anesthesia/neurophysiologist team allows for improved communication with the surgical and anesthesia teams in regards to IONM studies, adequate selection of anesthetic management and hemodynamic goals, as well as appropriate interventions when concerning signal changes occur (1,69). Our institution is a busy level one trauma hospital, stroke center and referral center for the Rocky Mountain region of the United States, performing approximately 1,400 neurosurgical procedures and 1,900 spine surgeries annually. The neuroanesthesiology team also provides coverage of IONM for over 1,600 cases a year.

Given the significant logistical considerations of an in-house IONM team, few anesthesia departments have capacity to supervise and interpret IONM. Often, IONM is performed by technologists supervised by a physiologist or neurologist either on-site or remotely (70). Because of our team's multifaceted role in patient care, we are positioned to impart expertise and education to interested physicians from around the world. Anesthesiologists and other physicians who have identified limitations in IONM in their working environments regularly reach out to our team for education and hands on training opportunities. Over the years, physicians from Colombia, Brazil and Scotland have spent time in our clinical environment to learn from an individualized curriculum geared towards neuroanesthesiology and IONM. The curriculum is based on neuroanesthesiology fellowship training guidelines from the Society for Neuroscience in Anesthesiology and Critical Care but can also reflect the specific interests of the individuals and the needs of the region they work in (71). Educational materials specific to neuroanesthesia, as well as in IONM, are provided to the visitors.

One case we wish to highlight was that of a Colombian anesthesiologist. He desired to improve the implementation of IONM in his home country on a more extensive and complete level. He spent six months with our team and participated in a curriculum of didactic lectures, journal clubs, seminars, morbidity and mortality conferences, and one-on-one planning and discussion of cases. The curriculum of topics specific to IONM included the review of relevant anatomy, technical aspects, effects of anesthetics. His experience in the operating room included anesthesia regimen planning, discussion and selection of IONM studies, needle electrode placement for the different IONM modalities, interpretation of baseline responses, continuous monitoring and discussion of interventions with the surgical team when alerts occurred. During his six-month experience, he had the opportunity to participate in 454 neuroanesthesia cases and the IONM care of 291 patients. His case log was diverse and included complex spine surgery, spinal cord tumor resection, supratentorial and posterior fossa tumor resection, awake cortical mapping, embolization of spinal cord tumors, among others. He also spent time at our affiliate pediatric hospital, Children's Hospital Colorado, and in the interventional radiology unit to enhance his overall experience.

IONM global expansion

Colombian experience

In a survey of Latin American spine surgeons, greater than 95% of respondents said IONM was indispensable or important for pediatric and adult scoliosis correction, thoracolumbar kyphosis correction, and intradural tumors (68). Despite the overwhelming endorsement, a majority of the same surgeons readily admitted that access to IONM is limited because of lack of service availability and cost. Colombia was represented in the survey and the conclusions in the paper mirrored what is routinely witnessed as an anesthesiologist, that a critical service for patient safety went unfulfilled.

After training at our institution for six months, he returned to Colombia and was met with numerous obstacles to broaden the use of IONM. While IONM is not new in Colombia, its use is very limited largely because of the unfamiliarity with the technology and its clinical application among surgeons and anesthesiologists (68). Few surgeons use IONM and most interpreters of IONM are physiatrists. Anesthesiologists often struggle with adapting anesthetic plans to accommodate for neuromonitoring needs because of an incomplete understanding of how various anesthetic agents impact the different IONM modalities (68).

Despite these obstacles that seem relatively easy to overcome with education, there are other significant obstacles. First, each local, regional, and national health system has different considerations when it comes to the implementation of IONM in patient care. Financial considerations are at the forefront of many health decisions. There is significant resistance from both hospital systems and insurance providers that precludes the use of IONM despite the potential benefits to the patient. Second, according to the ABRET database, no certified IONM technologists exist within the country. A lack of regulatory structure and absence of formal educational programs prevent qualified individuals from being trained. As a consequence, physicians who can administer and interpret IONM are in high demand. These individuals often travel throughout the country to provide this resource to patients on a request basis. Lastly, housing a dedicated IONM team at a single institution is impractical as many surgeons and anesthesiologists work at numerous hospitals, thus, equipment and supplies for IONM cannot be centralized easily.

Our colleague, with his acquired skill-set and knowledge, is making inroads toward increased implementation of IONM on a local level, but much more work is required for country-wide impacts. Educating surgeons on how IONM can be integrated into their surgeries and provide useful real-time data to guide their intervention has proven to be the most effective way to gain their confidence and improve their comfort with IONM (72). In the personal experience of our Colombian colleague, he is requested for surgeries of the spinal column, spinal cord, and brain tumor removal. Slowly, other types of vascular interventions and posterior fossa surgeries are utilizing his services. In his view, the expansion of IONM services in Colombia requires more robust education, primarily of hospital administrators and insurance companies about IONM's potential benefits to patient safety and operative outcomes. Additionally, the development of certified training programs must be a priority to address the shortage of technologists and interpreters. Perhaps, the most critical part of true country-wide expansion is the creation of a technologist pipeline. Developing national regulations on the position and creating an educational pathway for interested individuals are the first steps in filling the pipeline.

As might be expected, language proves to be a barrier as well. Most scientific literature on IONM is in English, and most training programs are also taught in English. The level of English proficiency in Colombian higher education is low and even less among those in primary and secondary schools (73). This can be a significant limiting factor to the training of new technologists and interpreters and should be a consideration when developing training programs. Even with this apparent disadvantage, scholarly work in IONM does originate in Colombia. Authors there showed that routine neuromonitoring in total thyroidectomy showed value in patients at high risk of recurrent laryngeal nerve injury (67). Even for motivated individuals, the costs to obtain training are important to consider and could be prohibitive. The costs of international travel, food, and lodging are weighed along with lost wages during the time of training. Despite Colombia's classification as an upper-middle income country, measures of poverty and inequality are comparable to those experienced in LMIC making it an impossible financial burden for many individuals in the country (74).

Uganda

Our team's interest in Global health is not bound by oceans or continents, an exciting frontier we are currently exploring is in Uganda. A combination of networking and good timing allowed one of our neuroanesthesiologists, to spearhead an effort to bring IONM to the CURE Children's Hospital Uganda (CURE International, Grand Rapids, MI, USA) in Mbale. Recognizing the supreme need for enhanced anesthetic care as well as the dearth of qualified clinical neurophysiologists and technologists in Sub-Saharan Africa, he fostered collaborations that led to the successful implementation of IONM capabilities. Utilizing similar methodologies: didactic learning, hands-on experience, and intensive training, coupled with remote assistance and consulting, he has now actively participated in nearly two dozen successfully monitored neurosurgical cases, including spinal cord detethering, posterior fossa tumor resection, and spinal cord tumor resection. Although the challenges to implementing this level of technology are many and legitimate, the rewards already far surpass these difficulties. Collaborating with native Ugandan clinicians promotes sustained and longitudinal successes, creates economic improvements through job generation, career satisfaction for clinicians interested in advancing their skills, and most importantly improves outcomes for patients. We look forward to sharing an expanded discussion on our successes in Uganda in a future publication.

Discussion

Neurologic disorders and injuries requiring neurosurgery are the second leading cause of death and disability adjusted life years lost in the world (75). Each year, approximately 14 million people require neurosurgical care, and of those, a significant portion would benefit from access to IONM (76). IONM is considered by many the standard of care for many spinal, intracranial, or vascular surgeries. This is true regardless of geographic location or socioeconomic status. Determination of which modalities are of the greatest value remains elusive, with no specific modality having been proven to be either 100% sensitive or specific for detecting injury. However, there is an increasing body of evidence supporting the use of combining different IONM modalities to increase the likelihood of detecting neurologic injury and preventing patient harm (77). Finally, of all surgical cases where IONM is utilized, minimal, if any controversy remains for its use in spinal cord tumors, with overwhelming evidence in favor of usage (78).

Surgeons will continue to drive the decision of whether or not to use IONM. A recent survey of spine surgeons showed that the most frequently reported reason for utilizing IONM was medicolegal, followed by surgeon reassurance, and lastly effect on patient outcomes (79). Certainly in a resource-rich academic medical center in the United States, the frequent use of IONM often seems obligatory to protect the surgeon from future legal action should an adverse outcome occur. However, our neuroanesthesiology group routinely experiences the value of IONM on patient safety and outcomes, particularly in patients who are at high risk of neurologic injury even before they enter the operating room. Moreover, when we sit down with patients to discuss our neuromonitoring plan, the reassurance that their safety is of the utmost importance to us is critical in improving the value of their care. No study, to our knowledge, examines what the patient perspective on the role of IONM is, however, we are certain that any reasonable person would wish for IONM to be utilized if they undergo surgery where injury their nervous system is possible.

We acknowledge that separating countries by economic status is an oversimplification of why IONM may or may not be used during surgery. Data from the United States alone shows a clear distinction between IONM utilization based on median income. In 2014, patients belonging to higher income groups had a nearly 80% IONM utilization rate while low-income groups had a rate of 20% (15). Not surprisingly, economics plays a central role in introducing and maintaining access to IONM in LMICs. Physicians, particularly anesthesiologists, are in a unique position to not only improve the lives of patients where they live, but also patients from around the world. In this review, we provided examples of the broader impact that can be made. Our in-person training of international physicians combined with external training and collaborations with diverse partners is evidence that, as anesthesiologists, our ability to help knows no borders. Our goal is to continue to improve patient outcomes by opening lines of communication promoting education and collaboration in IONM in areas where this resource is scarce.

Our appraisal of the literature is limited by several factors. First, we only selected papers already in English, or translated to English. Second, studies in the field of IONM lack randomized controlled trials because of ethical concerns, thus, robust inferences from study results are not possible. Lastly, every region or country has its own set of barriers preventing IONM implementation and assuredly other barriers we did not mention exist. Nevertheless, our hope is that this review provides the reader with food for thought and a greater insight into the challenges and potential benefits of implementing IONM around the world.

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