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Review

Neurological surgery: The influence of physical and mental demands on humans performing complex operations

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ABSTRACT

Performing neurological surgery is an inherently demanding task on the human body, both physically and mentally. Neurosurgeons routinely perform "high stakes" operations in the setting of mental and physical fatigue. These conditions may be not only the result of demanding operations, but also influential to their outcome. Similar to other performance-based endurance activities, training is paramount to successful outcomes. The inflection point, where training reaches the point of diminishing returns, is intensely debated. For the neurosurgeon, this point must be exploited to the maximum, as patients require both the best-trained and best-performing surgeon. In this review, we explore the delicate balance of training and performance, as well as some routinely used adjuncts to improve human performance.

1. Introduction

Performing neurological surgery is as demanding physically as it is mentally. It is then not surprising that neurological surgery has one of the longest and most rigorous training periods in medicine. In addition to the medical knowledge and procedural competence, neurosurgeons also must be trained to excel in the face of fatigue. Competence in this area is less tangible to observe and quantify, yet it deserves recognition as a core component of neurosurgical training and practice. Excellence in performance – whether for a shunt revision in the middle of the night or during the 14th hour of a complex skull base tumor resection – is necessary; there is little-to-no margin of error for neurosurgical patients. Herein, we evaluate different factors that contribute to the human aspects of performing neurosurgical operations.

2. Fatigue

Most studies relating to the effects of physician fatigue focus on resident physicians. This small proportion of the physician workforce is highly scrutinized and regulated in terms of their fatigue level. The Accreditation Council for Graduate Medical Education (ACGME) work-hour restrictions arose out of the concern that resident fatigue was leading to increased medical errors and complications. Medicine, and neurosurgery in particular, utilizes a complex neurobehavioral skill set in which a lapse in judgment or movement can result in significant adverse consequences. Therefore, physicians in a state of acute or chronic sleep deprivation may be more prone to commit an error, which leads to an adverse clinical event. Evidence for this is not lacking: a study of pediatric medicine residents' post-call performance on attention, vigilance, and simulated driving tasks demonstrated significant impairment similar to the performance level under the influence of alcohol intoxication.[1] Similarly, medicine residents demonstrated worse performance with a working memory task during call rotations than with non-call rotations.[2] However, in studies of surgical residents, findings of decrements in performance are less clear. On a surgical simulation task designed to require both cognitive and psychomotor skill, there was no significant difference in performance between pre-call and post-call neurosurgery residents,[3] although a similar task design administered to general surgery residents did exhibit significantly worse post-call performance.[4] No study evaluated different groups (specialties) directly, which made comparison difficult.

If fatigue does contribute to medical performance errors, they may not necessarily correlate with the occurrence of clinically significant adverse events. For example, surgery performed by thoracic surgery residents following an overnight operation had no significant difference in rate of patient morbidity, mortality, length of stay, or cross clamp or perfusion times compared to surgery performed by residents who had not operated during the preceding

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night.[5] The translation of fatigue into psychomotor impairment, and then into worse clinical outcomes of patients, is a second-order relationship that warrants further study.

Resident physicians, who have less experience and expertise, may be more susceptible to committing errors in a fatigued state; alternatively, the increased supervision of trainees may create a safety net that allows errors to be caught before they translate into adverse clinical events. Therefore, it is necessary to also examine the effect of fatigue on attending physicians – as they can serve both a supervisory and primary practitioner role. There is some evidence to suggest that sleep-deprived attendings may have worse patient outcomes. For example, a significantly higher complication rate occurred in daytime cases performed by attending surgeons who had operated the previous night and had slept less than 6 hours between the end of the night case and the beginning of the day case.[6] Similarly, cases performed by attending surgeons with less than 3 hours of sleep the preceding night had a higher rate of post-operative septicemia, although there were no other differences in complications attributable to sleep duration.[7] Other studies have demonstrated no significant difference in complications in surgeries performed by those attendings who were sleep deprived.[8,9] There are several possible explanations for the variation seen in these studies. One hypothesis is that surgeons who frequently operate in a sleep-deprived state become partially acclimated to doing so, and thereby develop the ability to function and avoid errors in this state. Studies reporting higher complication rates may be due to a larger numbers of errors committed by physicians representing specialties that have infrequent night cases. Another possibility is that systems factors may interact with individual fatigue. External factors, such as the assistance of residents and other members of the medical team, may offset any performance decrement due to fatigue in attending physicians. Overall, it appears that there is good evidence that sleep deprivation can contribute to impaired neurobehavioral performance. Whether this impairment translates into significant clinical effect is less clear and may depend on physician training, specialty, and hospital environment.

3. Operative timing

Not all neurosurgical operations are performed during the week and within "business hours". Emergencies require urgent and emergent intervention at all times. Scheduling considerations, particularly at high-volume academic centers, anecdotally increase pressure to perform elective surgery during non-routine hours. The question then arises, "are patient outcomes adversely affected by performing elective or selective surgery in the middle of the night?" Beyond night-time surgery, the question also arises if there is evidence that weekend surgery, or even surgery in July at the start of residency training programs, may present patients with unforeseen risk. These scenarios represent the complex interplay of patient-, surgeon-, and systems-based factors.

Beyond the potential contribution of surgeon fatigue as discussed previously, ancillary staff variation may have a significant role in the outcomes of "after hours" surgery. A single center study of the effect of operative time of day on outcome after liver transplantation found an alarming 7-day mortality rate that was twice as high in patients operated on at night.[10] Perhaps contributing to this finding was that overnight anesthesia and nursing teams were different from the daytime transplant-specific teams in the study.[10] Conversely, a database study found no difference in morbidity or mortality of cardiac transplant recipients operated on at night.[11] The high frequency of night-time procedures in this patient population may have led centers to develop systems for dealing with night-time surgeries, such as dedicated transplant operative teams. Dedicated teams that are specialty (or even procedure) focused appear to be effective in other types of surgery as well. A report on the effect of time of operation in elderly patients undergoing hip fracture repair found that patients operated on during the day had a lower mortality, but this decreased mortality was completely attributed to a dedicated trauma team and room during the day that had opened part way through the study period.[12] These findings suggest that the effect of operative time of day on patient outcomes may be partly due to specialized supporting resource availability, rather than surgeon fatigue.

In addition to night compared to day surgery, weekend *versus* weekday has also been studied. Patients admitted on the weekend with the diagnosis of spinal metastases were less likely to undergo surgery within 2 days of admission than patients admitted on a weekday, although the overall in-hospital morbidity and mortality were not associated with the day of the week of admission in that specific study population.[13] However, there is evidence that weekend admission is associated with higher in-hospital mortality in certain patient populations, such as for those with intracerebral hemorrhage.[14]

The "July phenomenon", the suspected relationship between the start of new resident training in the beginning of July and adverse patient outcomes, has also been debated. Patients undergoing spinal surgery for metastases at teaching hospitals in July have higher rates of in-hospital mortality, while at non-teaching hospitals, the rate of in-hospital mortality is significantly lower in this month.[15] There is also a higher rate of intra-operative or implant complications at teaching hospitals in July, while there is no significant difference in the rate of these complications in non-teaching hospitals in July.[15] There is also evidence to the contrary. Rates of mortality, neurological complications, and discharge disposition are not different in pediatric neurosurgery patients undergoing shunt operation or craniotomy for tumor resection in July or August compared to the other months.[16] Similarly, there was no difference in length of stay, resuscitation times, infection rates, or mortality of trauma patients admitted in July and August compared to those admitted in April and May.[17]

Surgery outside of routine business hours appears to have a significant effect on patient outcome in some but not other settings. These disparate findings are likely explained by differences in training of specialties, such as neurosurgery, that frequently operate during these times. No controlled analysis has yet been performed to account for this factor. Differences in systems-based factors such as operative team and residency program organization may affect patient outcomes.

4. Staging procedures

Another arena in which the effect of human performance may influence outcomes is lengthy, complex operations. In such operations, both patient and surgeon tolerance may be reached, affecting outcomes. One alternative to this is staging long surgeries into two or more separate operations. In skull base procedures, staged surgeries have been performed to achieve aggressive resection of extensive cranial base chordomas[18,19] and chondrosarcomas[20] with satisfactory results. One purported advantage of staging resection of extensive tumors is the ability to utilize two operative approaches, perhaps increasing the chance of achieving gross total resection (GTR).[20,21] Resection of large vestibular schwannomas has been staged with excellent rates of morbidity, long-term recurrence, and preservation of facial nerve function,[21,22] and may result in higher rates of GTR and long-term good facial nerve function than single stage operations.[23] While operative time and anesthetic considerations must be taken into consideration,[24] a distinctly human component must be considered for many skull base operations: in unstaged procedures, often the most challenging dissection of tumor from the brainstem occurs at the end of a long operation.[22,25,26] Therefore, the potential benefit of staging complex, lengthy operations may partly reside in an elusive human factor, by favoring a rested surgeon who is mentally and physically refreshed for the most critical portions of the procedure.

Staging has also been used as a strategy in the endovascular treatment of large arteriovenous malformations (AVM) and vein of Galen malformations (VGAM), as a way to limit single-session radiation doses, single-session operative times, and rapid changes in lesional hemodynamics. Additionally, staging is useful in the pediatric population, who can tolerate only a limited volume of contrast agents.[27] Staged embolizations have been used effectively in the treatment of AVM, pial arteriovenous fistulae, and VGAM.[28–31] In comparison to skull base tumor resections, staged embolizations appear to have significant patient-centered benefits, in addition to minimizing operator fatigue.

Staged procedures have also been used in spinal surgery, where they may decrease the risk of complex procedures and allow for multiple operative approaches.[32] In scoliosis, staged surgeries may help to reduce the risk of neurologic compromise.[33] In one study of single compared to multistage procedures in patients with scoliosis, single-stage procedures had more blood loss and longer surgical time, with complications directly related to operative time.[34] In that series, elderly patients tolerated single-stage operations better, suggesting that the benefits of breaking longer procedures into multiple days may depend on both patient and surgeon characteristics. However, other studies have found no difference in outcomes (equivalent curve correction and morbidity) with either one- or two-stage anterior and posterior spinal fusion for scoliosis. This study noted increased overall and intensive care unit lengths of stay with two-stage procedures.[35] The choice to stage an operation does not assume a single surgeon. In one study that found significant advantages of single-stage anterior/posterior fusion, (including greater curvature correction and decreased morbidity), the two parts of the operation were performed by different surgeons.[36] This supports the hypothesis for the contribution of surgeon fatigue to worse outcomes in single-stage procedures in other studies of anterior/posterior spinal fusion. In addition to mental fatigue, which is less quantifiable, muscular fatigue increases linearly with the length of the operation, and contributes to increased hand tremor.[37] While patient characteristics such as anesthetic time and degree of physiologic changes may contribute to the beneficial effect of staging procedures, physical and mental stamina of the surgeon may be an important human performance factor in complex operations and is inherently variable.

5. Ergonomical adjuncts

Some aspects of operations cannot be altered; for example, surgeon comfort must not compromise patient positioning for operative exposure. Other aspects of operating are modifiable, such as surgical instrument design. This can have an impact on the surgeon that may alter performance. For example, forearm muscle flexion or extension can affect grip strength, tools can cause neurovascular compression resulting in numbness and decreased performance, and suboptimal instrument design can lead to increased muscle fatigue.[38] Several strategies have been developed to help overcome these effects. Ergonomic considerations in surgical instrument and equipment design may help reduce fatigue and increase safety for both patient and surgeon. Tools specially designed for microneurosurgical procedures may allow reduced retraction with increased mobility and visualization, allowing the surgeon to perform better.[39] Measures other than neurosurgical instrument design have also improved surgeon comfort (aiming to reduce fatigue). Simply inclining the microscope foot switch subjectively improved ease of use and comfort and resulted in optimal muscle group usage as measured by electromyography.[40] Another simple item that can improve surgeon comfort is using gel foot pads to stand on. These decrease discomfort and the number of times surgeons stretched or took breaks.[41] The changes in discomfort were present both immediately postoperatively and a full 24 hours after the operation in which they were used. There were also more perceived errors when the gel pads were not used, suggesting that discomfort may distract the operative team and impact performance.[41] Other factors, such as chair and armrest design, may affect fatigue and stability and influence the ability to perform sustained complex procedures.[42,43] Even surgical loupes and the operating microscope have been designed to decrease surgeon neck strain and fatigue.[44,45] Ergonomic advancements are vital to human performance in non-surgical situations, such as aircraft cockpits,[46,47] offices,[48] spacecraft,[49,50] assault rifle design,[51] air traffic controller working environment,[52] commercial truck driving,[53] and law enforcement.[54] Innovative design and refinement of operative tools may help to push the limits of human performance by reducing muscle strain and fatigue in surgery and can draw on the comparative experience and innovation found in other fatigue-prone scenarios.

6. Other adjuncts to neurosurgical procedures

Multiple components of the operative environment can combine to reduce the strain on the surgeon in an attempt to reduce performance deficits. One less acknowledged factor is the presence of a co-surgeon. Two surgeons may work effectively together, assisting and complementing each other's skills. In brachial plexus surgery, two surgeons working simultaneously have decreased the total length of the procedure and, in turn, anesthetic and infectious risk.[55] Other adjuncts include the use of a neurosurgery specific operative checklist.[56] This type of checklist, and checklists in general, may be able to help to prevent wrong site, wrong procedure, and wrong patient events.[57] Also to be considered is the simple act of the surgeon taking a break when tired. In complex laparoscopic operations in children, taking a five minute break after every 25 minutes of working did not increase operative time and resulted in decreased surgeon cortisol levels, decreased strain and pain, and improved performance scores.[58] Importantly, more intraoperative adverse events were observed when breaks were not taken.[58] This provides further evidence that surgeon performance may be impacted by human factors such as fatigue and concentration.

Noise in the operating room may also influence surgeon performance. Noise is ubiquitous during neurosurgical operations, with sources including suction, anesthetic monitoring devices, and high-speed drills. Music is often played at the preference of the surgeon to sometimes mask noise or provide psychological comfort. In study subjects operating simulated operative tasks using a robotic surgical system, music had a significant beneficial effect on economy of motion and surgical speed.[59] This effect was most pronounced when either hip-hop or Jamaican style music was played, suggesting that high-rhythmicity genres may have an added benefit.[59] Other studies of music and simulated surgical performance have shown significantly improved surgical memory consolidation when music is played.[60] When looking specifically at the effect of music on surgeon physiological responses (autonomic reactivity), a benefit was most appreciated for surgeon-selected music compared to experimenter-selected music, both of which showed an improvement compared to the control conditions of no music.[61] While this music should not impair communication between members of the surgical team, music can help improve surgical performance.

7. Pharmacological countermeasures

Pharmacologic substances have been studied and used in other industries such as aviation and the military to improve alertness and psychomotor performance in the fatigued state. Caffeine, a commonly used stimulant in our society,[62,63] has been studied in the military for its performance enhancement effect under conditions of sleep deprivation and physical fatigue. In a shooting task, strategically dosed caffeine decreased the time to detect and shoot at a target following strenuous physical activity, without impacting shooting accuracy.[64] Caffeine also improved accuracy and response time in cognitive tasks in a group of US Navy SEALs in training under conditions of extreme sleep deprivation and physical exhaustion.[65] In the medical field, caffeine improves sleep-deprivation-induced decrements in time taken and economy of movement on a laparoscopic surgery simulation task. The addition to caffeine of taurine, a substance commonly used in energy drinks, had similar benefits as well as a slight improvement in error rates.[66]

The ability of dextroamphetamine and modafinil to improve alertness has been studied as well as caffeine. All three drugs reverse the decline in psychomotor vigilance performance seen with extended sleep deprivation to near baseline, although the three substances have different durations of action, potential for abuse, and side effect profiles (with caffeine having the shortest duration of action and most side effects).[67] All three have benefit in military aviation applications; they are routinely utilized on long duration missions.[68] Further study is required to determine whether these same benefits apply to neurosurgical training and practice, conditions where demanding tasks in the setting of similar sleep deprivation are present.

Apart from neurocognitive countermeasures, pharmacologic aids have also been studied to reduce tremor. Physiologic tremor reduction is possible with the beta blocker propranolol and it has been evaluated in surgical settings. In ophthalmic surgeons holding a surgical instrument, propranolol had a significantly greater reduction in physiologic tremor than placebo.[69] Propranolol also significantly reduced self-perceived tremor in ophthalmology residents performing ocular microsurgery.[70] Propranolol has a long history of use in performers and athletes, as well.[71] These studies suggest that it can enhance human performance in microsurgical operations by decreasing tremor and increasing movement precision. Pharmacologic adjuncts may also both compensate for the negative performance effects of sleep deprivation and enhance performance in the resting state. However, use of these substances is limited by serious potential negative effects and requires further study before their use can be recommended in surgical practice.

8. Substance abuse and other psychosocial variables

Psychological and social factors outside the workplace may affect how physicians perform. Physicians who are not in complete psychological health may perform suboptimally. Substance abuse has been of particular concern in the medical field. With stressful jobs and access to controlled prescription substances, physicians may be at increased risk of substance abuse. American physicians have a lifetime substance abuse rate of approximately 8%.[72] They are more likely to use alcohol and controlled prescription medications than the general population and less likely to use cigarettes and illicit substances.[72] Younger healthcare providers are more likely to abuse alcohol or drugs,[73] and female physicians are at especially high risk of alcohol use compared to age-matched female non-physicians.[72] Surgeons may be at even higher risk of substance abuse, with one survey identifying a 15% rate of alcohol abuse among surgeons.[74] Among this population, female gender and shorter work hours were associated with increased rates of alcohol abuse.[74] Importantly, surgeons with alcohol abuse or dependence were more likely to report having committed a major medical error recently.[74] Identifying and addressing risk factors for substance abuse is important to improving both physician performance and patient safety.

Psychosocial dissatisfaction such as burnout and depression may also have an important role in physician performance. Factors that may contribute to surgeon burnout include conflict between expectations and responsibilities at home and at work, resolving such conflicts in favor of work, increased work hours, and female gender.[75] Alcohol abuse is also associated with a higher rate of burnout.[74] Such feelings of dissatisfaction are important, as there is a high co-occurrence between self-perceived medical error occurrence, burnout, and depression.[76,77] The relationship between medical errors, burnout, and depression appears to be such that perceived errors also tend to engender future perceived errors by creating psychological distress.[77]

Another factor, physical activity (particularly in physically active individuals), has been associated with performance improvement in tasks of sustained attention.[71,78] Similar studies have demonstrated neurocognitive improvement in both relatively young[79] and old[80] subjects. It is unknown whether the same results would apply to surgery and other fields where persistent attention is necessary for the successful completion of a task. Regardless of this specific direct outcome, exercise has improved psychological health and ability to manage stress in a range of subjects,[81–83] something that is invaluable to peak surgical performance.

9. Training limitations

A fundamental aspect of neurosurgical training is that fatigue is unavoidable. Once outside of the residency training period, there is no limitation to how many hours one may be required to work, or at what intervals. At some point, all neurosurgeons will perform operations when tired, frustrated, and stressed. A counter philosophy exists that it is better to embrace these physical and mental struggles as realities. Much like a distance runner, one experiences physical distress during training to prepare for similar conditions.

Many neurosurgeons would argue that neurosurgical training occurs over a lifetime, not just during a residency period. However, distinct limitations exist during the formalized training period to improve patient safety by preventing resident physician fatigue. In 2003 the ACGME, acting in response to mounting public pressure, instituted a new set of rules that regulate the number of hours that residents may spend working in the hospital. Included in the current rules are the requirements that residents may not work more than 80 hours per week (88 hours for some programs requesting a special exception), must have one day off from clinical duty per week, and may not work generally more than 24 consecutive hours (Table 1).[84,85] These rules apply to residents in all specialties, from radiology to pathology to neurosurgery. In surgical subspecialties, such as neurosurgery, residents traditionally have worked long hours to both gain the knowledge and hone the skills necessary to gain competence in their field. Some would argue that the ability to perform in the face of fatigue is developed with this type of training (and is consequently compromised by work-hour restrictions). The balance between providing excellence in clinical care, obtaining adequate training, and fatigue is yet to be perfected and may not be a static constant across all residents or specialties. The new work-hour regulations provide an interesting opportunity to study these issues in neurosurgical trainees.

The response to the ACGME work-hour regulations has been mixed in the neurosurgical community. In a survey of neurosurgery residents and residency program directors performed soon after the regulations were introduced, most respondents felt that

Table 1
Resident physician work hour restrictions (after the ACGME work-hour restrictions; effective date July 2011[85])

Maximum weekly hours of work	• 80 hours averaged over 4 weeks • Exceptions allowing up to 88 hours may be given for programs providing educational rationale
Maximum consecutive working hours	• 24 hours of patient care activities plus 4 additional hours for educational and transition of care activities • PGY-1 residents are limited to 16 consecutive hours of patient care
Time free from clinical responsibilities	• Minimum 1 day per week averaged over 4 weeks
Minimum time off between working periods	• 8 hours, with 10 hours recommended • 14 hours following 24-hour in-house call
Maximum call frequency	• Every third night, averaged over 4 weeks

ACGME = Accreditation Council for Graduate Medical Education, PGY-1 = postgraduate year 1.

both patient care and resident training experience were negatively affected.[86] While this survey had a low response rate, predisposing the study to bias, the findings largely agree with current sentiments. A report sanctioned by the Society of Neurological Surgeons, the American Board of Neurological Surgery, and the Residency Review Committee for Neurological Surgery (the organizations associated with neurosurgery resident education), expressed great concern about the potential implications of further restriction of resident work hours, citing the importance of advanced technical skill development and continuity of patient care.[87] A more recent survey of neurosurgical residents found that most respondents felt that the new, more stringent, guidelines for interns would decrease resident educational experience and increase patient care errors.[88] This survey, however, also found that 5.3% of respondents reported committing a major error resulting in patient harm after working more than 24 hours,[88] suggesting that some serious consequences to working extended shifts may need to be considered.

While there are many opinionated viewpoints of work-hour restrictions, objective evidence that outcomes have changed as a result of them is less prevalent. Two high-profile studies showed that internal medicine interns following an investigational schedule that eliminated work shifts longer than 16 hours received more sleep and had fewer attention failures than interns following a traditional work schedule with overnight call every third night.[89] Notably, interns following the interventional schedule also committed significantly fewer significant medical errors.[90] However, there was no significant difference in the rate of adverse events between the two schedules, largely because most intern errors were picked up and corrected by other team members. Additionally, there was no significant difference in the rate of procedural errors committed between the two schedules. This suggests that while extended work hours may lead inexperienced trainees to commit more errors, safety nets are built into teaching hospitals that catch most of these errors before they affect patients.

In surgical specialties, some evidence suggests that work-hour restrictions negatively affect patient care. One study that reported the experience of a single residency training program found that the rate of morbidity in all neurosurgical patients increased after implementation of reduced work hours.[91] This finding has been replicated in studies using a nationwide database, showing increased mortality in patients admitted to teaching but not non-teaching hospitals after work-hour reform for coronary artery bypass graft surgery,[92] hip fracture,[93] and neurosurgical trauma.[94] Additionally, the resident American Board of Neurological Surgery written exam scores have declined since the introduction of restricted work hours,[95] suggesting the potential negative impact of reduced time spent in patient care on resident knowledge.

Contributing to the negative impact of work hours on resident education is the traditional structure of neurosurgical training programs, where residents provide a large amount of patient care. In efforts to reorganize this structure and comply with work-hour restrictions, resident education may be compromised. For example, residents have experienced an increase in the percentage of time spent on call with a commensurate decrease in the proportion of time spent in conference and the operating room as a result of work-hour restrictions.[95] Further organizational changes may improve resident education while operating within these constraints.[96] For example, employing allied health practitioners to assist with patient care may allow residents to spend more time in the operating room while satisfactorily managing patient care needs.[97]

Conflicts of interest/disclosures

The authors declare that they have no financial or other conflicts of interest in relation to this research and its publication.

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