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HISTORY OF MEDICINE

Technological Innovation and Ethical Response in Neurosurgery

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Introduction

Neurosurgery has a rich tradition of experimentation and innovation. These efforts are stimulated by a human desire to understand our anatomy, our consciousness, and ourselves. Experimentation with our brain and thoughts offers vast opportunity matched by significant ethical and physical risks [1]. In this manuscript, we explore the history of innovation in neurosurgery with a focus on the life cycle of learning, including associated ethical challenges and resolution. Our purpose is to illuminate the intersection of neurosurgery, innovation, and ethics so that history can inform a rational approach to future neurosurgery advances.

A bit of background is needed to properly explain cycles of innovation. In health care, as in other industries, there are periods of technology expansion and periods of technology refinement [2]. The drivers for rapid expansion typically include enabling technologies and societal needs [3]. For example, late in the twentieth century, wide availability of miniaturized processing power, solid-state storage media, and powerful communication infrastructure set the stage for rapid development and adoption of smart mobile phones. Although individuals helped bring these changes about, it was the enabling technology and societal desire for instant and constant access to data and people that created fertile conditions for technological innovation. Similarly, enabling technology and societal need define periods of rapid technology expansion in other fields.

One difficulty in innovation is that periods of technology expansion tend to create or exacerbate ethical challenges. With smart mobile phones, for example, concerns about privacy, unequal access, and censorship have increasingly become global discussions [4]. Ethical challenges are highlighted or precipitated by technological advances, and the path to resolution of those challenges can be slow. Decades into mobile phone availability, efforts to solve ethical and practical challenges require ongoing public and private debate. In health care and the field of neurosurgery, given their direct influence on lives and health, ethical dilemmas are both immediate to the patient and of deep concern to society.

Leveraging the Past to Understand the Present

While it is beyond the scope of this brief article to discuss neurosurgery history and ethics comprehensively, considering two periods of rapid advancement may offer insight into innovation cycles. We will examine the late nineteenth century and mid-twentieth century periods of rapid technology expansion, how these expansions led to ethical challenges, and how those challenges were addressed.

The late nineteenth century was a period of rapid expansion of medical technology in all specialties, with a great deal of experimentation and innovation in neurosurgery specifically. Factors that contributed to this state of affairs included improved communication facilitated by the industrial printing revolution [5], pain-free operations made possible by the advent of anesthesia [6], and improved surgical safety using antiseptic techniques [7]. These led to robust experimentation and innovation in neurosurgery. Bell and Magendie's experiments in 1868 established the anterior-posterior anatomic relationship of motor and sensory function in the spinal cord and ushered in the modern era of neurophysiology [8, 9]. In 1874, Robert Bartholow conducted a series of controversial experiments on Mary Rafferty, a patient with a cranial defect resulting from an ulcerating tumor that allowed him to perform direct brain stimulation. These experiments confirmed that the parietal lobe was responsible for motor control of the contralateral limb and that seizures came from irritation of the human cortex [10]. But Rafferty's death and ambiguity about informed consent raised questions about the ethical appropriateness of such medical research.

By the end of the nineteenth century, there was a strong populist movement against human experimentation [11]. Topics of global debate included the Neisser syphilis inoculation trial [12], criminalization of physician intervention without consent in some countries, and appropriate experimentation practices [13].

In the mid-twentieth century, another period of rapid neurosurgical advancement and innovation occurred. Enabling technologies included electrocautery, which allowed safe dissection of the scalp and control of intracranial vasculature [14]; roentgenography, which made it possible to image surgical neuroanatomy [15]; and electroencephalography, which provided imaging of functional neurophysiology [16]. Enabling technology coupled with societal drivers led to innovation and experimentation. Nazi Germany is well known for medical research war crimes [17], but ethical lapses in proper consent and insufficient respect for autonomy were pervasive across the globe [18, 19]. From the Tuskegee syphilis experiment to the 22 experiments with no patient benefit highlighted by Henry Beecher [20], intellectual curiosity overwhelmed ethical concerns.

In response to these ethical failures, ethical principles of human experimentation were codified in the Nuremberg Code in 1947 [21], the Helsinki Declaration in 1964 [22], and, in the US, in Henry Beecher's seminal article on pervasive unethical medical practices in 1966 [20] that ultimately led to the 1979 *Belmont Report: Ethical Principles and Guidelines for the Protection of Human Subjects of Research* [23]. For the first time, a global framework for ethical human experimentation was developed and enforced. This new ethical framework prioritized potential benefit for the individual, rather than the greater good for society [24].

The two periods outlined above exemplify cycles of innovation that included a set of enabling technologies, followed by rapid advances in medical practice, resulting in recognition of new or newly understood ethical challenges, followed by a decades-long struggle to understand, define frameworks for, and implement solutions to those ethical dilemmas.

Looking Toward the Future

The past can serve as a roadmap to the future. History should give pause to the emerging innovator who enters a field during a time of rapid expansion. Based on today's enabling technologies and societal drivers, neurosurgery is very likely entering another such period of rapid expansion. Newly available enabling technologies include devices that capture and store extensive clinical data, vast computational power, and tools to analyze genetics and gene expression. A resurgence of societal support for neurosurgery innovation is underway, with enthusiasm from academics, physicians, and even the federal government in the form of the BRAIN initiative [25]. While the full spectrum of errors we will make can only be conjectured, new ethical dilemmas are certain to come. In this section, we examine a selection of likely neurosurgical innovations. Again, the goal is not to be comprehensive, but rather to share the flavor of the newest cycle of advancements and potential ethical challenges.

One likely advancement is the advent of the clinically effective brain-computer interface (BCI), first discussed in 1991 [26]. Considerable preliminary success has been achieved. Experiments using a penetrating microelectrode array in humans have established control of robotic arm prostheses [27]. Limited motor control of robotic prostheses has been achieved through subdural nonpenetrating electrode arrays that do not damage the cortex [28]. Cognitive prosthetics are being developed that actually improve the ability to encode new memories [29].

As these interventions become increasingly feasible, questions arise about how more sophisticated BCIs will be tested and to what purpose they will be applied. New nanomaterials are making direct connections between single neurons and electronics possible [30]. Would a future direct neuroelectronic interface with neuroanatomic networks that influence our conscious and subconscious minds make us something other than human? On a more practical level, could extension of rudimentary language decoding through brain-computer interfaces [31] be employed to establish autonomy in patients with locked-in syndrome? If such an interface were to decode subconscious thought, how might we preserve privacy and autonomy with these devices? Is it possible to establish decision-making capacity prior to experimentation on those with cognitive BCIs that are partially responsible for the ability to make decisions or create memories? What is the role of the physician in assessing the outcomes of such interventions?

Other ethical issues are raised by restorative neurotherapies that focus on treating disease: stem cell therapy for stroke [32] and neurodegenerative disease [33] and deep brain stimulation for alcohol addiction [34, 35] and obsessive-compulsive disorder [36]. Rapid expansion of experimentation in an attempt to treat currently incurable diseases will lead to ongoing questions of clinical equipoise and therapeutic access.

These and many other innovations in neurosurgery represent tantalizing but concerning opportunities. Can knowing that there will be ethical challenges help us to foresee problems today and potentially improve the field's approach to a period of rapid technical expansion?

Conclusion

The past is our best guide to understanding future challenges [37]. History teaches us that periods of enabling technologies and societal support stimulate rapid progress that precipitates new moral dilemmas. It seems likely that we are entering such an exciting and ethically challenging period in neurosurgery. The ethical questions of our era will not be the same as those in past history, but common themes abound. We continue to try to understand and define humanity, assure appropriate protections for the vulnerable, and promote broad access to advanced interventions within a financially stratified society.

If history is any indication, today's neurosurgery will be judged as much on its ethical approach as on its clinical success. How can we, today, work to deserve the respect and appreciation of future generations by understanding and incorporating lessons learned from the past?

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Disclosure

Daniel Riskin is CEO of Vanguard Medical Technologies and Founder of Health Fidelity.

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