Engineering and Innovations in Neurosurgery

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ABSTRACT

Introduction: Modern technology engineered and developed with artificial intelligence have significantly improved the nature of diagnosis and treatment of patients. Healthcare facility has changed significantly in the past few decades because of technological developments. Neurosurgery has been able to practise and enjoy a lot of technologically advanced tools in the past few decades. In context of Nepal, technologically sophisticated devices and tools ranging from neuro navigation, high speed cutting drills, intra operative neuro monitoring, deep brain stimulation, to high resolution magnetic resonance imaging are already introduced. In this paper, the literature review on currently available technologies used in neurosurgery, their significance in delivering a better health care and their usage in Nepal has been discussed.

Keywords: Innovation; Neurosurgery; Technology.

INTRODUCTION

Biomedical engineering (BME), the integrated field of study that implies the application of engineering principles and designing concept to medicine and biology for healthcare purpose. This discipline aims to bridge the gap between engineering and medicine by merging engineering's design and problem-solving talents with medical and biological sciences in order to improve healthcare treatment, such as diagnosis, monitoring, and therapy.[1–3] The field of biomedical engineering in the current scenario plays a vital role in improving the medical diagnosis and treatment. Different from other discipline of engineering, BME have the knowledge of both electrical circuits and components as well as human anatomy, physiology and biomechanics, which has helped them to integrate the knowledge of engineering to develop implants and machineries required for the diagnosis and treatment.[4,5]

Neurosurgery being one of the most complicated surgery and requires a lot of tools and technologies for the efficient and better outcome after the surgical procedure. With this regards, biomedical engineering is highly becoming an important part in neurosurgery. The clinical practice of neurosurgery has been radically transformed by modern technologies.[6] Patients are implanted with active and passive devices or treated with improved microsurgical instrumentation for a range of ailments. Following surgery, these patients are transferred to modern intensive-care facilities equipped with the most up-to-date patient monitoring and computer technologies.[7] The responsibilities of biomedical engineers have gone beyond simple equipment/system installation and maintenance.

Technological advancement in medical care might be characterized as the presentation of another innovative device or procedure that starts an adjustment or changes in existing of clinical practice. Neurosurgery being one of the delicate and complicated surgical procedures, this requires a lot of modern and technologically advanced devices and tools. The technological advancement in neurosurgery has been seen with the development of modern radiology, which includes high resolution MRI images able to locate even the smallest of the nucleus in the brain, functional MRI to identify the various active spots in brain, fibre tracking and so on. With the development of new technologies and tools, advancement in surgical procedures can be seen, the technologies that has been able to upgrade the neurosurgical practice has been discussed in this paper.

Innovations in Neurosurgery

Imaging modalities in Neurosurgery

The development of modern imaging technologies have given rise to new imaging modalities for clear and distinctive visualization of brain structures. In general, CT is better suited for an evaluation of certain structures such as the lung parenchyma, airways, bowel, and cortical bone, whereas MRI is more useful for the evaluation of internal architecture of other structures such as the bone marrow, muscles, tendons, ligaments, cartilage, deep brain structures.[8] Depending on the need of the disease prognosis, CT and MRI both are equally important tools in neurological studies. However, the evolution of 3T and higher intensity MRI has helped the neurosurgeons and neuroscientist for the better visualization of deep brain structures and their functioning patterns. Conventional CT and MRI images have been helping the neurologist and neurosurgeons to diagnose and treat various brain and spinal related diseases and disorders. With the developing imaging technologies and complex engineering, CT and MRI images have drastically changed from the time they were introduced.[9]

MRI in the past decade has evolved in such a manner that MRI images not only provide the structural analysis of the brain but MRI images now has been able to interpret the way the human brain functions. Functional MRI (fMRI) provides functional information by visualizing cortical activity. fMRI detects subtle alteration in blood flow in response to stimuli or actions . For an instance if a patient is commanded to move his right hand during the acquisition of MRI images, the functional MRI detects the region of the brain with high flow of blood, hence providing the information to the surgeons about the region of the brain responsible for movement of the hand.[10] Such imaging and diagnosis has helped the surgeons to protect the area of the brain responsible for the motor functioning during the surgical procedures hence leading to better surgical outcomes.

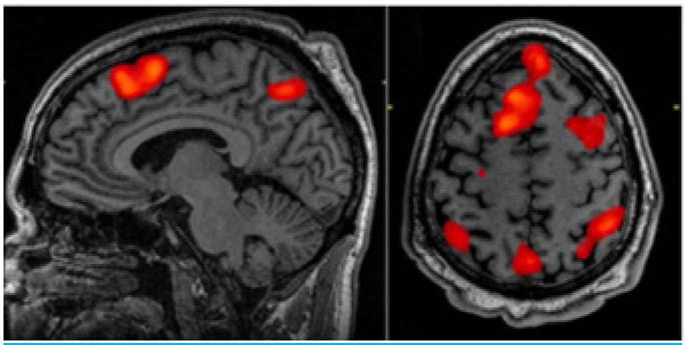

Figure 1: Functional MRI with active areas of activation

Similarly, Diffusion tensor imaging (DTI) in MRI is another imaging modality available for the brain scans. DTI uses anisotropic diffusion to estimate the axonal (white matter) organization of the brain, that is, DTI images provides the information about the neurons and fibres in the brain. With the help of 3D reconstruction of DTI images Fibre tractograghy can be obtained which provides the insight about the neural tract of the patient. The colour coded tracking system uses, red, green and blue fibres to represent transverse, anteroposterior and craniocaudal fibres respectively.[11] Based on these data and information, the assessment of the deformation of white matter by tumor can be gathered.

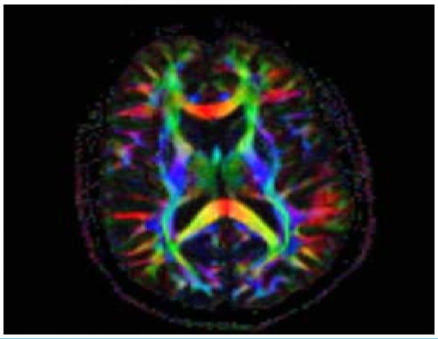

Figure 2: DTI images showing white matter fibre

Cine MRI is another imaging modality developed to capture the dynamic image of the brain. The Cine MRI is generally used to observe the flow of Cerebrospinal Fluid (CSF) and is useful tool in diagnosing the extent of chiari malformation. Although, using the conventional MRI images Chiari can be diagnosed, with the use of Cine MRI the extent of Chiari can be quantified based on the volume of CSF being flown out of the ventricle in each heartbeat.[12]

Skull Bone implant

Till date, a wide range of materials has been utilized for the reconstruction of bone imperfections ranging from human and non-human bone grafts to metals, ceramics, and polymers. Polymers are of high priority since they are generally simple to process and are available in reasonable price. Materials like Polyethyl-ether ketone (PEEK), Polymethyl methacrylate (PMMA) and hydroxyapatite (HA) are the most commonly used polymers for the repair of the cranial repair.[13,14]

The use of PMMA as cranial implant material dates back to 1940s. In past, PMMA was moulded intraoperatively by surgeons themselves to create an implant of desired shape and size. Intraoperatively moulded PMMA prostheses require complex strategies, for example, planning of the blend with direct contact with the dura mater that can create exothermal responses or produce harmful chemicals during the surgical procedure, setting time for PMMA leads to prolonged operating time.[15] Also to add on, in case of larger cranial defect, the contour cannot be maintained thus leading to poor aesthetics. But with the development of technology and modern tools, the computer assisted designing and fabrication method are being used. The computed tomography (CT) images are used for the reconstruction of the cranial defect, subsequently producing the plastic or metallic based implant model which is moulded to create a PMMA implants. Computer assisted design and prosthetic material modelling has resulted in an excellent cosmetic outcome, and reduce operating time necessary for implant placement.[16]

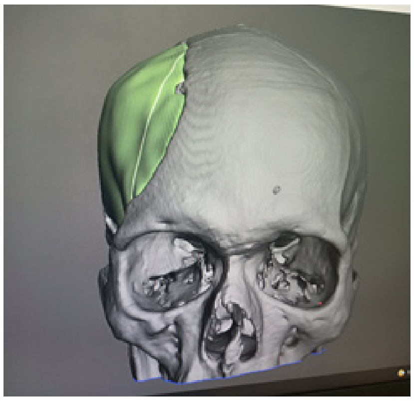

Figure 3: 3D based customized implant designing

With the growing use of technologies and advancement machineries, prefabricated and 3D modelled titanium and stainless steel implants are also being widely used. The Netherlands based implant manufacturer Xilloc has been designing the customized patient implants made out of titanium. However, the higher cost of the technology hinders the use of such technologies in the developing and low income countries like Nepal. In such scenario, as discussed earlier Poly lactic acid (PLA) plastic based 3d printing and PMMA moulding can be a better suited option. PMMA based customized 3D printed bone implants have been designed and implanted in Nepal as well. More than 25 cases with symmetrical outline, contour and without any post-operative complications like infection have been performed in various neurological institutes of Nepal.[15]

Robotics in Neurosurgery

Automation, machine learning and robotics have been the major technological breakthrough in the field of engineering in the 21st century. The field of neurosurgery is too being pulled into such technologies with the introduction of surgical robots and tools.[17] Technological developments in imaging guidance, intraoperative imaging, and microscopy have pushed neurosurgeons to the limits of their dexterity and stamina. The introduction of robotically assisted surgery has provided surgeons with improved ergonomics and enhanced visualization, dexterity, and haptic capabilities.[18]

Looking back to the history, first robotic assisted neurosurgery was performed in 1985 by Kwoh and colleagues, where they used Programmable Universal Machine for Assembly (PUMA) for holding and guiding the biopsy cannula. The same system was then used by Drake and his team as a brain retraction system in 1991 for operating thalamic astrocytoma. Started from mid 1980s various robots and automated system has been designed and practiced in neurosurgery.[19] Tele-surgical robots, the supervisory surgeon controlled robot, handled shared or controlled systems are some of the most recent and commonly used surgical robots in neurosurgery.[20]

The tele-surgical robots allow the surgeons to remotely control the movement of the robotic arms. The Neuroarm developed by university of Calgary, Canada mimics the movement of the surgeon's hand using piezoelectric motors and has 8 degree of freedom. This system has integrated tactile feedback system that allows the surgeons to have the real feel of the tissue and tumours.[21] Similarly, the supervisory surgeon controlled robots like Minerva and pathfinders allow the surgeons to precisely perform stereotactic surgeries either with frame or without the frames. These are mostly used in guiding the biopsies needle, electrodes into deep brain structures and also in the spinal surgery to insert the pedicle screws.[22] Furthermore, handheld shared or controlled systems allows the surgeons to jointly control the instruments to manipulate and resect the brain structures. These system integrates the precision of the robotic system and skills of the surgeons. The Steady hand system developed by John Hopkins University is one of the examples of the handheld shared robotic system. NeuRobot, developed by Shinshu University, Japan and ROSA robotic system by Medtech Zimmer are the robotic arm consisting of forceps and micro-instruments that can be highly useful in brain dissection and tumour resection.[20]

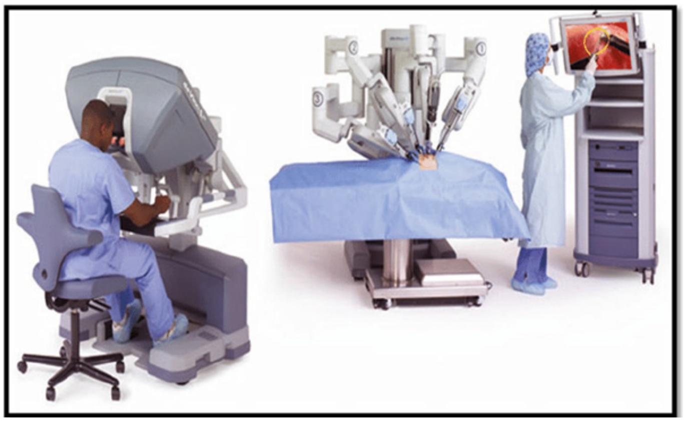

Figure 3: 3D based customized implant designing

With integration of robotic system in neurosurgery, surgeons are allowed to navigate to the deep brain structure without having much harm to healthy brain. The precise hand movement and tremor and error free design has helped to upgrade the overall quality of the surgery and complete excision of tumor, better targeting for biopsies and electrode placement in deep brain structures.

In the present scenario, robotic surgery are way too expensive for the low economy country like Nepal. However, the first neurosurgical robotic system compatible with neuro-navigation has been recently introduced in Kathmandu Medical College and Hospital (KMC hospital) by Medtronics.

Neuro Navigation

Neuronavigation is the technique designed to assist neurosurgeons precisely localize various intracerebral pathological processes by using a set of preoperative images (CT or MRI). The operation of brain diseases requires the accurate localization of lesions and the prevention of damage to key structures.[23] Despite the advancement of numerous techniques such as angiography, MRI, sonography, and frame-based stereotaxy, a more precise localizing methodology is still required.[24] Neuronavigation has become a standard of care in contemporary neurosurgery since more than two decades. The development of computer assisted localization of brain structure was possible only after a significant technological progress, especially in the area of informatics and imaging.[25] Introduced for the first time during late 1980s, neuronavigation has gained a lot of popularity among the neurosurgeons worldwide in present context.[26]

This complex technology depends on the registration of patient's facial or spinal structure and superimposing it on the images from CT/MRI. The computer software then shows equivalent MRI images in all section (axial/coronal/sagittal) of where the surgeon has pointed to, helping the surgeon know about the specific area of the operative site and degree of tumor resection. It likewise assists with distinguishing the right approach and the degree of opening needed, before the surgery. Surgeons are continually directed with regards to the position of their instruments all through the surgery especially during the spinal surgery and at the time of placing the screws in the spine.[27] Neuronavigation likewise helps in keeping the skull openings of craniotomy small and in limiting the harm to healthy brain.

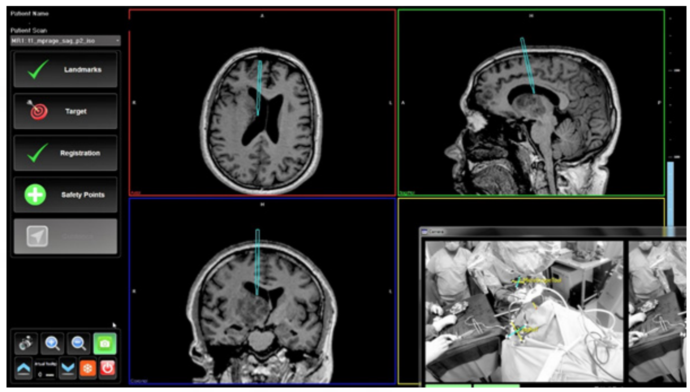

Figure 5: Neuronavigation used in excision of Glioma.

Although, neuro navigation technology seems to be expensive, complicated and out of reach in context of Nepal, different companies have already introduced neuro-navigation system in Nepal. Medtronics, Brainlab and Happy reliable surgical (HRS) are some of the commonly used neuro navigation system in different hospitals of Nepal. They allow the intraoperative tracing of brain and spine based on their software used.

Deep Brain Stimulation

Deep brain stimulation (DBS) is one the elective surgical procedure performed to treat various brain abnormalities. The brain can be compared to a complex electric circuits consisting of different active and passive components, in this sense the abnormality expect for the morphological changes in the brain can be explained as mismatch or the failure in any electrical components, which eventually leads to chemical imbalances within the brain and body. With this regards, the abnormal activity in brain can be corrected by placing the leads to specific locations in the brain and rectifying the electrical impulses generated at that location.[28] This procedure of externally applying the electrical impulses just to correct the functioning of the brain is known as DBS. These electrodes are place on the specific nuclei in the brain depending on the presentation and symptoms of the patient and is connected to an active batteries generally placed subcutaneously at chest (below the clavicle). Usually performed to treat movement disorders, DBS was first introduced in late 1980s. Approved by FDA in 2002, DBS has been reportedly performed in more than 1 million patient with Parkinson's disease. But with the development of technology and introduction of dual lead stimulators, DBS has been researched and performed in patients with obsessive compulsion disorders (OCD), depression and psychiatric patients as well.[29]

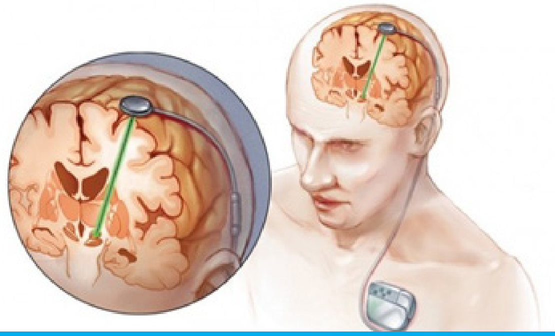

Figure 6: Diagrammatic representation of lead placement and pulse generator for DBS.

Despite the complexity surgical procedure and precise localization of target is required, DBS has been introduced in Nepal as well in 2014. Although there is a single institute, Annapurna Neurological Institute and Allied sciences have been performing DBS and Pallidotomy, more than 80 patients with PD and other movement related disorder (essential tremor, dystonia, and task specific focal dystonia) have been treated with this sophisticated technology.[30,31]

Recently the modern and the advanced form of DBS, has been researched and is being used as clinical trials known as Magnetic Resonance Imaging Guided Focused Ultrasound (MRgFUS). MRgFUS is based on the principle of DBS, which aims the portion or the nucleus in the basal ganglia or any other structure in the brain using a MRI image and the targeted location is stimulated via a focused beam of ultrasound.[32] This non-invasively targets the desired location in the brain and the high intensity focused ultrasound creates a lesion in that location causing the disruption of the electrical path which was initially the cause of abnormal functioning of the brain. In other sense, MRgFUS is the non-invasive form of Pallidotomy, instead of making a burr and inserting radiofrequency (RF) probe and creating a lesion with RF, MRgFUS uses the focused beam of ultrasound to create a lesion in the desired location.[33]

Intraoperative EEG and Neuro-monitoring

Intraoperative neurophysiological monitoring has been used in attempts to limit neurological deficit during the surgical resection of tumor or brain pathologies. The objective of such monitoring is to figure out the abnormalities of brain and is found mostly useful during the epilepsy surgery. Intraoperative Electrocorticography (ECoG) was first introduce and used in 1940s by Wilder Penfield and Herbert Jasper for localization of lesion and abnormal areas in epilepsy surgery.[34] The development of new and sophisticated amplifiers, and recording electrodes, the functional and epilepsy surgery has advanced too far to detect the signal from a single neurons.[35] The invasive and implantable, subdural or depth electrodes able to record brain waves directly in contact with brain have been developed and used in epilepsy surgeries.

Intraoperative neurophysiological monitoring (IONM) evaluates the integrity of neural structure and network during surgeries. It incorporates both consistent checking of neural tissue as well as helps in localizing the vita nerves. The objective of IONM is to distinguish intraoperative neural damages that permit early intervention to eliminate or to essentially limit irreversible harm to the neurological tissue and prevent the possible deficit or weakness after the surgery. Various modalities of IONM are available ranging from somatosensory evoked potential (SSEP), motor evoked potential (MEP), brainstem auditory evoked potential (BAEP), and visual evoked potential (VEP).[36] In past, the monitoring system with a single model were available but nowadays the multimodal monitoring devices are widely available and is being used in various spinal and cranial surgeries. Since the introduction and use of IONM in neurosurgery, it has reduced the chance of paralysis, hearing loss, muscle weakness, and loss of other functions.

DISCUSSION

Technological advances have altered almost every part of our lives from the way of communication to transport and in every day to day activities. But the technological advancement in the field of health care is still in shadow and is not much talked about. Engineering has been playing a vital role in serving healthcare and bringing about some revolutionary advances in healthcare.[37] Correct use of technology and analytical tools with unprecedented power (such as artificial intelligence and machine learning) will reduce costs, extend the reach of health care services, and save lives. Engineering advancement and technological upgradation in healthcare has always been focused towards reduction of treatment cost, better and efficient treatment and improve the way patient receives the treatment.[38] Neurosurgery being one of the delicate, complicated and critical field of medicine, this field has been able to witness may of the technologically sophisticated and most advanced form of medical devices and technologies.[6] From the tissue engineered products like artificial dura repair to the one of the most complicated technology of function MRI is often used in neurosurgical practice.[39] The use of Gigli's Saw which took hours for craniotomy to the use of high speed, precise and sophisticated neuro drill, there has been significant technological advancement in neurosurgery. With introduction of each technology, there has been significant improvement with respect of patient disease diagnosis to the care and post-operative outcome.[40] 3D modelled patient specific implants, functional MRI, Stereotaxy and Deep brain stimulation surgeries, Intraoperative neuro-monitoring, neuro navigation systems have already being introduced in Nepal as well. From 2014, Annapurna Neurological institute and allied sciences have been using the technology of Deep brain stimulation, with this hundreds of people with the PD are able to have better quality of life. The recent installation of robotic surgical arm in Kathmandu Medical College and Hospital (KMC hospital) can be considered as the technological breakthrough in developing countries like Nepal.

CONCLUSION

Modern tools and technologies developed by integrating the engineering concept with the improved surgical and analytical technique have been widely used in the field of neurosurgery in the past two decades. These tools and technology have been able to upgrade patient safety, reduced surgical and recovery time due to minimally invasive and non-invasive procedures.

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