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REVIEW ARTICLE

Neurosurgery Simulation-based Skills Training: From Mannequins and Cadavers to Virtual Reality and Artificial Intelligence

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Abstract
Simulation in the neurosurgical context broadly refers to systems that either create or enhance the perceivable and sometimes interactable environment of the user. Adequate resident training requires hands-on experience, but operative neurosurgery affords few such chances. Moreover, the pressure of performing well, time constraints and fear of mistakes hinder adequate learning. It may also lead to an erroneous evaluation of the residents' surgical aptitude on the part of the supervisor. Simulation systems offer a unique solution for resident training in a safe environment as well as unbiased evaluation. Simulation-related technologies can also be used to better counsel patients, pre-operative planning and development of newer techniques and devices. Various modalities of simulation training available at present include physical (PR), virtual (VR), augmented (AR), and mixed (MR) reality. Though we have achieved significant advances in all forms of simulation models, largely we are dependent on human experts for the evaluation of the performance of trainees. Artificial Intelligence (AI) algorithms may offer an alternative to human experts with several advantages including the removal of human bias, and preserving human resources. In this manuscript, we have summarized our innovations and lessons learned from our neuro-engineering collaboration at the Neurosurgery Education and Training School (NETS): Neurosurgery Skills Training Facility (NSTF), All India Institute of Medical Sciences (AIIMS), New Delhi that will help in pushing the boundaries of the role of simulation in neurosurgery.

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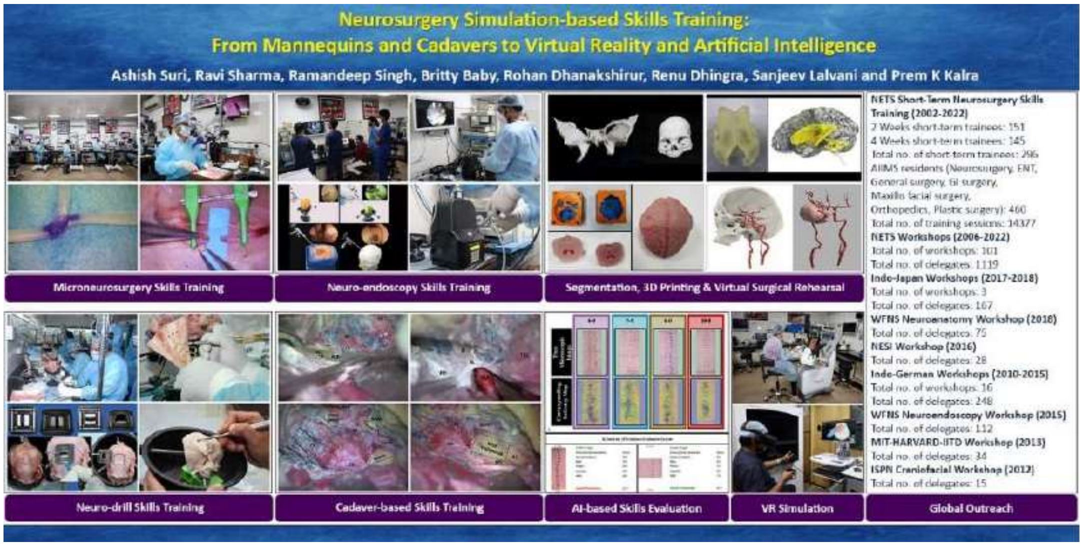
Graphical Abstract



Background of Neurosurgery Training

There has been a paradigm shift from the old Halstedian apprenticeship-based teaching model being practiced in the past. There are several reasons for this, including reduced teacher: student ratio, reduced working hours of residents, financial and medico-legal constraints in the operating rooms. Along with this, supervised training by expert neurosurgeons although essential, as the sole training modality could induce anxiety, subjectivity and unquantified learning. Neurosurgery being a challenging specialty with morbidity can be intimidating for both teachers to teach and students to learn. Iatrogenic injuries are being increasingly recognized, with a need for additional training post formal neurosurgical certification [1,2]. In Low and Low Middle Income countries (LMICs), there is a dearth of trained neurosurgeons to cater to the need of the large population [3]. Majority of institutions providing training in neurosurgery lack the infrastructure for holistic skills training such as cadaver lab, animal facility and simulation training. This is compounded by lack of a standardized training curriculum. Although, creating and grooming a neurosurgeon is rigorous, resource intensive and time consuming as it is a long road, there is a severe need felt for neurosurgery skills training facilities in India. There is approximately one neurosurgeon for every 250,000 population in India with close to 230-250 neurosurgeons being trained each year. Nearly 31% of the institutes with neurosurgery training programs in India have not published peer-reviewed papers in the last 5 years [4-5].

Origin of the Neurosurgery Skills Training Facility

The Experimental Micro-Neurosurgery Laboratory at the Department of Neurosurgery, All India Institute of Medical Sciences (AIIMS), New Delhi was started in 1971 through the efforts of the stalwarts of Indian Neurosurgery - Prof. P. N. Tandon and Prof. A. K. Banerji. It was intended to be a nexus of neurosurgery skills training and imparting of practical knowledge to future trainees. It has since evolved into a state-of-the-art multifaceted Neurosurgery Skills Training Facility (NSTF) with crucial roles in skills training, cutting edge research and evolution of biomedical engineering in neurosurgical simulation (Figure 1).

Pioneering work is being done in the fields of developing and standardizing an objective structured modular neurosurgical skills training curriculum, virtual reality (VR) application in training, artificial intelligence (AI) usage in evaluation of training, developing physical models for task-based training and creation of virtual repository of computer assisted design (CAD) models of neurosurgical devices [6,7]. Objective assessment of skills and standardization of curriculum is evolving across neurosurgery [8] and the role of simulation in neurosurgical education and training is expanding constantly [9–15] and our facility is contributing to it as one of the pioneers.

A unique and indispensable arm of the NSTF at AIIMS, New Delhi is the Neurosurgery Education and Training School (NETS); a holistic training effort undertaken by intramural inter-departmental collaboration between the departments of neurosurgery, anatomy, forensic medicine and central animal facility with extramural experience injected by national and international dignitaries in the field of neurosurgery. Its workshops provide in-depth skills training, along with refinement of neurosurgical understanding in a holistic context.

The quality of training being imparted at our skills training facility is showcased by the large number of trainees from outside AIIMS who apply for short term training (STT). The far-reaching impact of the research work being done within and beyond neurosurgery is evident by the collaboration of the NETS with the departments of Biomedical Engineering and Computer Science Engineering at the Indian Institute of Technology (IIT), New Delhi.

Simulation training and research are intricately tied up in the NETS-NSTF with training sessions providing background and data for research activities which in turn are applied for betterment of the training modules. There are multiple carefully designed modules with physical and/or virtual simulators for task and procedure-based simulation training in various facets of Neurosurgery.

Figure 1. Overview of neurosurgery simulation-based training at NETS-NSTF.

Simulation in Neurosurgery

Simulation based training in neurosurgery comprises of the different modalities of simulation viz physical, virtual and mixed reality low and high-fidelity simulators. Human and animal cadaveric models, live small experimental lab animal models, custom designed mannequins, bench trainer models and state-of-the-art virtual reality simulators with task and procedure-based simulation are available and routinely utilized in our lab. The performance of subjects is assessed objectively with expert feedback and automation to improve ability to generalize and eliminate bias. Computerized AI based automated, objective assessment coupled with sensor based kinematic assessment of skills leads to holistic assessment causing the learning curve to flatten. The various simulation modalities available at our lab are summarized in Table 1.

Microneurosurgery Module

Microsuturing: Three levels of complexity are used to provide structured task-based microsuturing physical simulator training with expert feedback and AI based evaluation. The 'Basic' level entails introduction to microsuturing ergonomics and proper technique with meticulous expert intervention to teach novices the basic tenets of microsuturing. It involves supervised 4-0 and 5-0 suture size microsuturing. The 'Intermediate' level is where the trainees expand their horizons by working with finer suture sizes – 7-0, 8-0, 10-0, and where the requirements and evaluation of the task-based training exercise are more stringent. The 'Advanced' level is where the trainees start training in physical simulator task-based exercises on mico-anastamosis of nerve and vessel models. It starts with orientation and expert feedback provided on physical simulator models such as silastic tubes followed by progression onto animal models such as chicken wing arteries and finally live animal models such as live anesthetized rat/guinea pig nerve and vessels (Figure 2A). At all levels of training, constant expert feedback and supervision is provided to help trainees develop the proper technique and learn from their performance. This is supplemented with AI based objective, unbiased and instant performance scoring for standardizing training for all trainees. We have developed a Deep Learning-based automated performance scoring system with ranking which can automatically and accurately segment the suture line from a provided picture of the final sutural construct and give overall and parametric scores. This AI-based system has been trained on expert feedback-based ground truth evaluation of thousands of sutural constructs, thus making it very close to accurate.

Microneurosurgery: Physical simulators have been created emulating various neurosurgical procedures for procedure-based and task-based training with expert supervision and feedback supplemented by automated AI segmentation and assessment. Various simulators available are for aneurysm dissection and clipping, and cadaveric skull base approaches. State-of-the-art VR modules with multiple training exercises with in-built evaluation and feedback augment the training provided in our lab- NeuroVR for brain tumor surgery eg. glioma and meningioma excision, laminectomy, etc. and ImmersiveTouch for ventricular catheterization and pedicle screw fixation. (Figure 2B). The trainees are also exposed to finer microneurosurgical nuances on cadavers especially for skull base approaches (Figure 2C).

Table 1. Summary of various simulation modalities available at NETS-NSTF

S. No.	Name of the Skill Lab	State	Management	Courses and Duration
1.	Neurosurgery Education and Training School (NETS), Neurosurgery Skills Training Facility (NSTF), Department of Neurosurgery, AIIMS New Delhi.	New Delhi	Government	**Neurosurgery** **2 weeks & 4 weeks short-term simulation based skills training.** **(Recommended 3 sessions of two weeks or 2 sessions of four weeks in MCh/DNB Neurosurgery)** **Microneurosurgery Module** 1. Microsuturing • Basic: 4-0, 5-0 • Intermediate: 7-0/8-0, 9-0/10-0 • Advanced: Silastic tube, Chicken wings artery, live anasthesized rat/ guinea pig vessel/nerve anastomosis 2. Microneurosurgery • Aneurysm Clipping • Cadaveric Skullbase Approaches • Physical Simulator with AI-based Skills Evaluation • Virtual Reality **High-Speed Drilling Module** • Basic: Sheep head, Scapula • Intermediate: Microscopic/Endoscopic Drilling • Advanced: Neurosurgery Craniotomy • Physical Simulator with AI-based Skills Evaluation • Virtual Reality **Neuroendoscopy Module** • Basic: Natural Simulation, Mannequin • Intermediate: Neuroendoscope Box Trainer • Advanced: Cadaveric Endonasal Approaches • Physical Simulator with AI-based Skills Evaluation • Virtual Reality **Spine Instrumentation Module** • Saw bone • Virtual Reality **Clinical Observership** • Ward/ICU rounds • Operative room (OR) Observership **Case Scenarios** • Video-based training

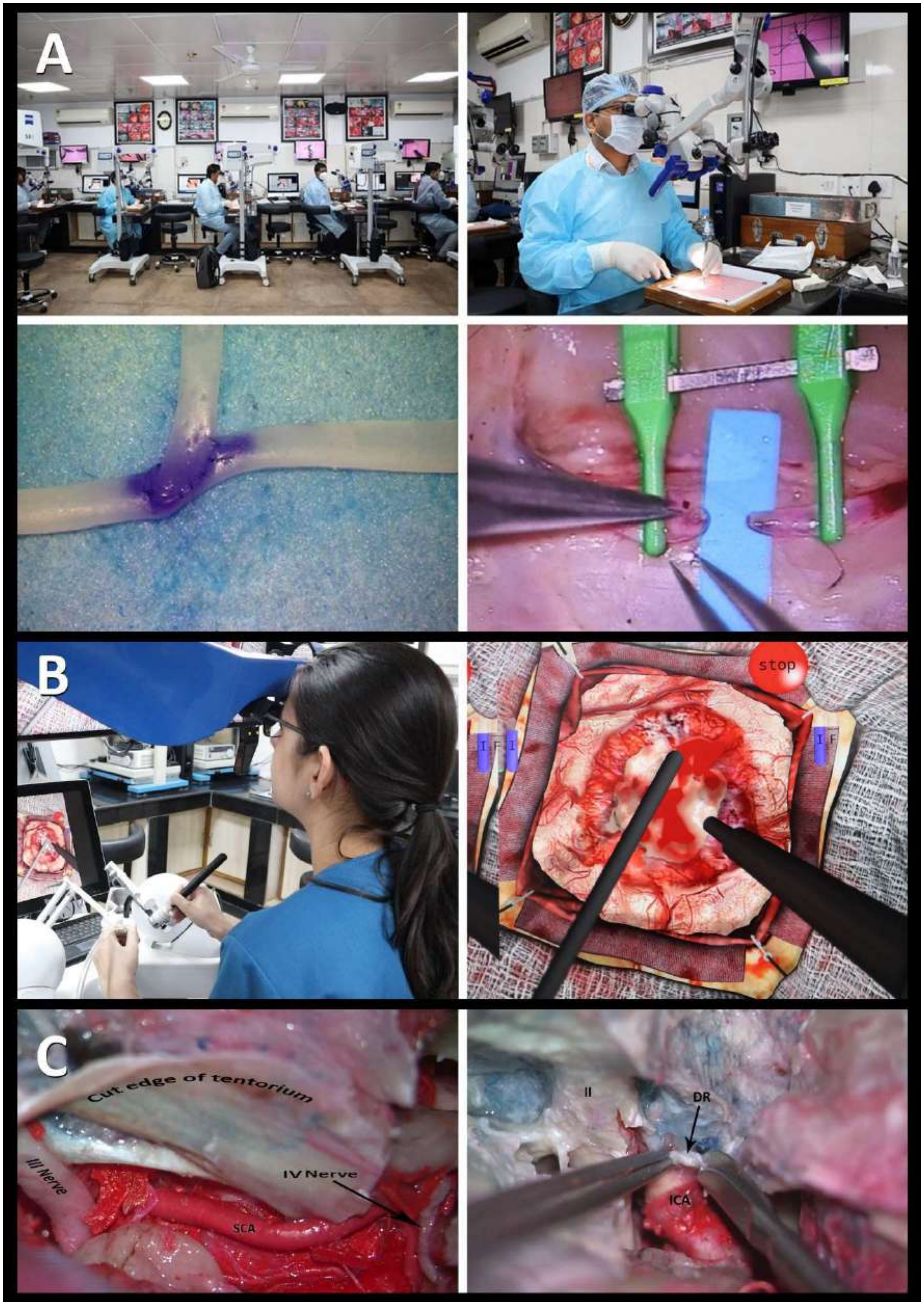


Figure 2. Various microscopic simulation modules- A. Microsuturing, B. Virtual reality based microneurosurgery, C- Cadaver-based microneurosurgery.

High Speed Drilling Module

Neurosurgical drilling is an integral part of cranial as well as spinal surgical procedures. The NETS-NSTF provides cutting edge and world class physical and virtual reality simulators for accurately emulating and assessing microscopic and endoscopic drilling. Three levels of drilling training are provided to trainees; 'Basic' entails orientation to drill handling and ergonomics with constant expert supervision and feedback followed by macroscopic task-based training on cadaver sheep head and scapula specimens; 'Intermediate' level incorporates microscopic and endoscopic drilling with familiarity and ease of handling being a focus with the change in visualization methods. The 'Advanced' level emulates real world application of drilling with neurosurgical craniotomy simulation with expert feedback on the adequacy, speed and safety of the craniotomy (Figure 3A). This is augmented with AI based automated, objective skills evaluation and ranking which has been trained on hundreds of expert ground truth evaluations. The NeuroVR haptic feedback simulator also has a module for microdrilling hemilaminectomy. (Figure 3B) The 'Advanced' level neurodrilling training exposure is further enhanced by supervised cadaveric workshops conducted at our lab (Figure 3C).

Neuroendoscopy Module

When endoscopic interventions were introduced in neurosurgery, they initiated a revolution of minimally invasive neurosurgical procedures. As these procedures require a different skill set in terms of orientation and planning as compared to traditional microneurosurgery- NETS-NSTF has developed original, custom-designed and open-source training modules with a structured training regime incorporating self, expert and AI based feedback. As with microsuturing and drilling, endoscopic simulator training is also structured into different levels with trainees perfecting the learning objective of one level to incorporate all the skills required to benefit maximally from the subsequent level. This provides them with self-feedback and a smoother learning curve. The 'Basic' level teaches safe and ergonomic endoscope handling, assembly and disassembly along with orientation to the 2-dimensional screen space- enabling trainees to recreate a 3-dimensional projection of the same. This is followed by task-based training with expert supervision and feedback in natural and mannequin physical models for endonasal as well as intraventricular procedures. In the 'Intermediate' level, trainees are introduced to and familiarized with our cutting-edge in-house physical simulator for neuro endoscopy training- the Neuro-Endo-Trainer [19–22]. (Figure 4A) It enables evaluation of the ease and ergonomics of bimanual endoscope and instrument handling. It also has a movable platform thus simulating the various angles at which anatomic structures present themselves during actual procedures. It entails a task-based structured training regime amenable to AI auto-segmentation and objective automated scoring with different levels of difficulty to enable the trainee to learn through self-feedback on a continually improving pace. Automated evaluation of Neuro-Endo-Trainer performance with AI based segmentation of instrument tip and auto tracking of task completion and steps taken has been developed in our lab. Electromyography based assessment of tremors and correlation with neurosurgical skills has also been undertaken at our lab. The systems for tracking the tip of the endoscopic operating tool in 3D space by exploiting the rigid body properties of the tool and dry bone have also been developed which enable precise endoscopic skull base interventions. NETS-NSTF also provides NeuroVR based endoscopic third ventriculostomy (ETV) virtual reality simulation training with haptic feedback. (Figure 4B) After adapting to bimanual handling, variable angles and 3D projection of the 2D space, trainees progress to the 'Advanced' level where cadaveric endonasal approaches are taught under constant expert supervision. (Figure 4C).

Spine Instrumentation Module: Both physical saw-bone and virtual reality simulators with expert feedback are provided in our lab for task and procedure based spinal instrumentation training.

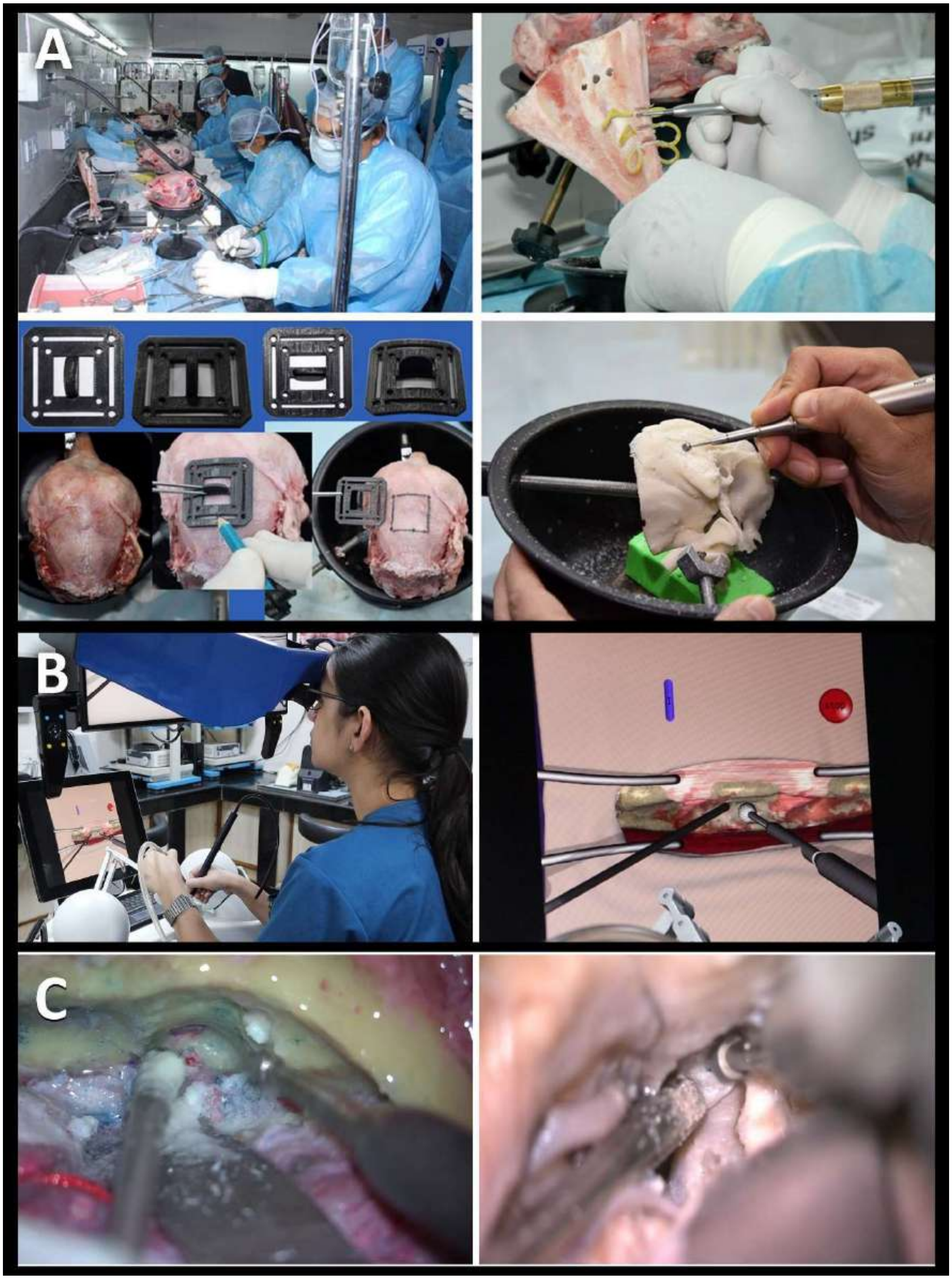


Figure 3. Various high-speed neurodrilling simulation modules- A. Microdrilling, B. Virtual reality-based microdrilling, C- Cadaver-based microdrilling.

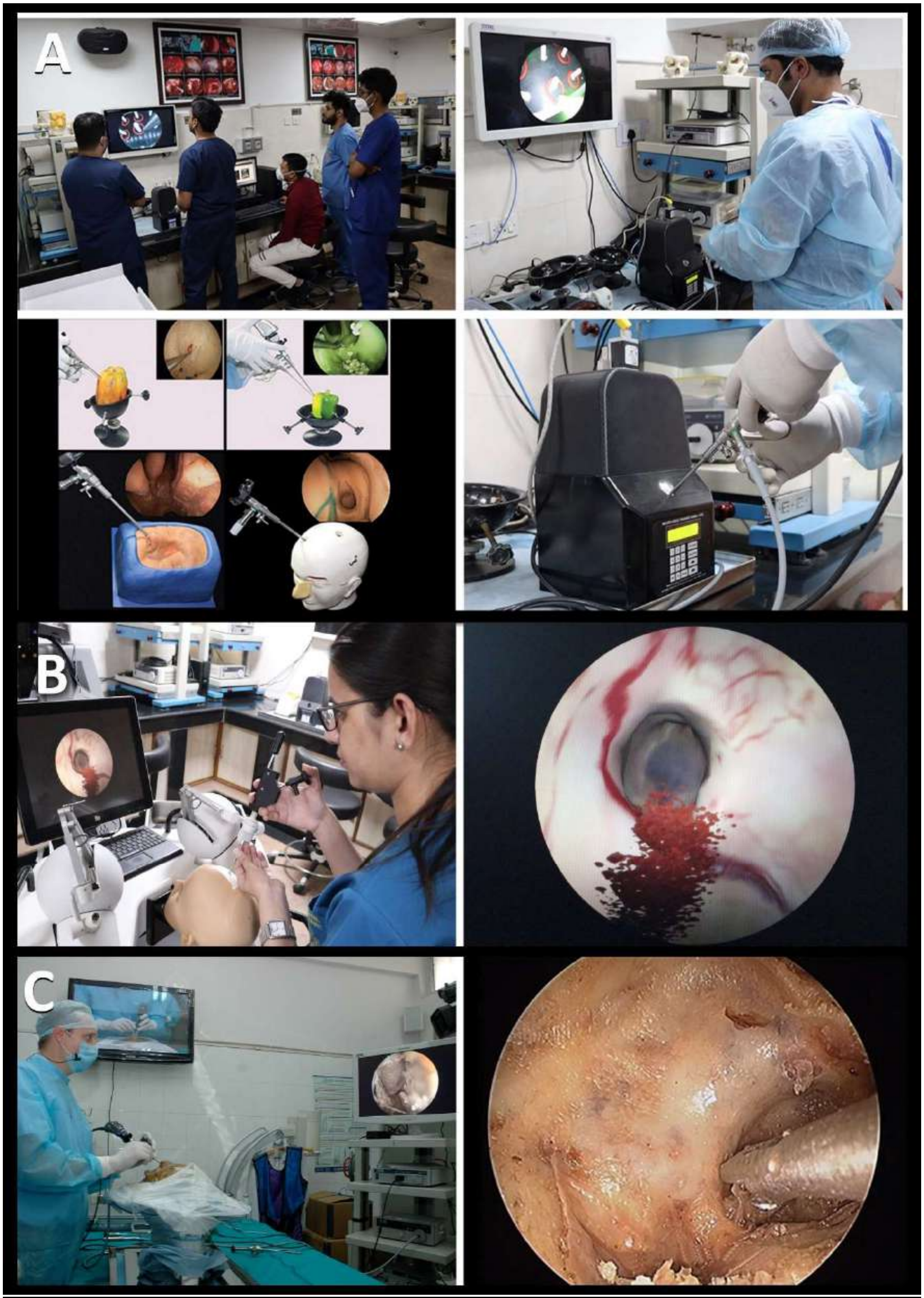


Figure 4. Various neuroendoscopic simualtion modules- A. Neuroendoscopy , B. Virtual reality based neuroendoscopy, C- Cadaver-based endoscopic approaches.

Table 2. Various Components of AIIMS-NETS-SAS

S. No.	Criteria	Evaluation parameter	1	2	3	4
1	Eye hand coordination	-Handling of instruments (Needle holder, forceps, endoscope, grasper) -Depth perception (under magnification)	Continuous struggle throughout the activity	Frequent loss of coordination	Grossly smooth coordination	Perfect coordination
2	Instrument tissue manipulation	-Tissue handling under magnification with various instruments -Appropriate pressure and force -Confrontation with neighboring objects (Repeated puncture)	Grossly unacceptable	Frequent difficulty	Smooth handling	Perfect manipulation
3	Dexterity	-Tremors/ jitteriness -Therblig (intraoperative elemental motion)	Irregular therblig/ tremors/ jitteriness throughout the activity	Frequent difficulty	Grossly smooth	Perfect dexterity
4	Flow of procedure	-Time management during activity -Total duration in task completion -Unnecessary delays in inter or intra therblig	Grossly unacceptable	Frequent lapses	Grossly smooth	Perfect flow
5	Effectualness	Evaluation of end result on predefined criteria* for: -Microsuturing -Neuroendscopy	Grossly unacceptable	Partially acceptable	Grossly acceptable	Perfect end result

*Criteria for effectualness	
Microsuturing • Margins (overlapped/loose/apposed) • Inter-sutural distance (equal/unequal) • Sutural distance on both sides of the incision (equal/unequal) • Angulation between suture and knot (Near perpendicular- Yes/No)	**Neuroendoscopy** • Final position of rings 1. >= 3 rings slipped 2. 2 rings slipped 3. 1 ring slipped 4. All rings in place

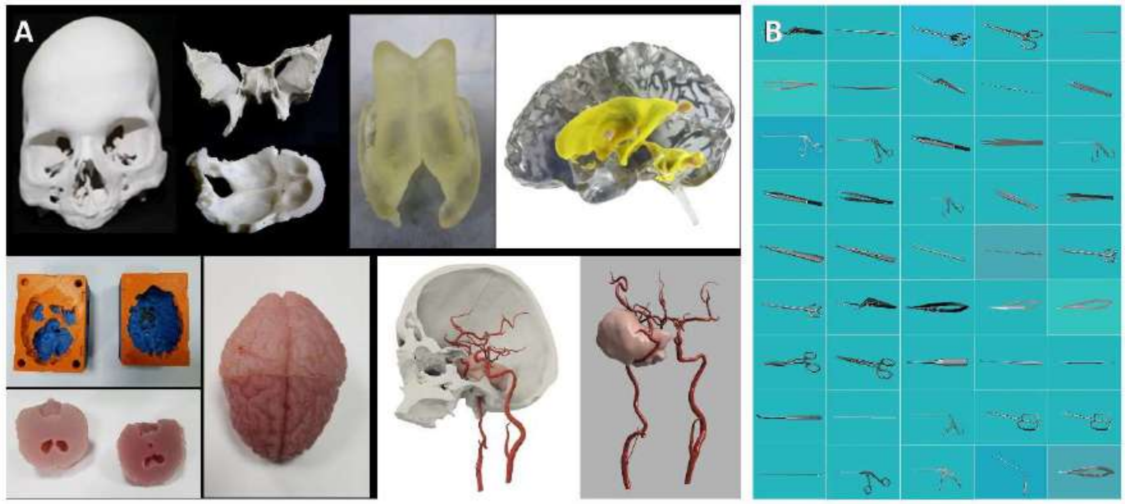


Figure 5. A. CAD based 3D-printed models, B- Virtual surgical instrumentation repository.

Development of scoring system NETS-SAS

We have developed an in-house expert objective scoring system for a holistic and objective evaluation of neurosurgical skills. Their development has been tested with AI for automation which provides multi-dimensional assessment and avenues for feedback. The Neurosurgery Education & Training School – Skills Assessment Score (NETS-SAS) has been summarized in Table 2 and it has been validated in previous studies [6,14].

Development of unique physical simulators

NETS-NSTF has developed, tested and compared unique synthetic physical simulator material simulating skin and dura mater using silicones. The hardness of our various in-house silicone mixtures was measured and neurosurgical opinion after practicing micro suturing on the material was used to determine the best mixture, which was haptically closest to simulating skin and dura mater.

The NETS-NSTF has a 3-D printing facility for developing various in-house 3D CT/MRI segmented biomechanical and anatomically accurate physical models for various procedure-based training such as aneurysm clipping and skull base models [16] .We have also developed scanned CAD models of various neurosurgical instruments for 3D space manipulation, which also enables creation of more elaborate simulations [17,18] (Figure 5A-B).

International Collaboration

International workshops and conferences:
Collaborative training with multi-departmental and multifaceted workshops are being continually held and facilitated by our lab. Since 2006, there have been 101 NETS collaborative workshops with 1119 total delegates. Multiple professional neurosurgical bodies such as the World Federation of Neurosurgical Societies (WFNS) and International Society of Pediatric Neurosurgeons (ISPN) have held their benchmark workshops at our facility. Short term training (STT) 2 weeks and 4 weeks courses for participants working and training in neurosurgery outside AIIMS, New Delhi are being constantly chosen by many trainees from all over the country. There have been 296 total short-term trainees and 14377 total STT sessions. (Figure 6).

Indo-German Collaboration:

NETS-NSTF was instrumental in Indo-German collaboration neurosurgical training workshops involving the Ministry of Science & Technology, Govt. of India and the University of Mainz with dignitaries and stalwarts such as Prof. Martin Bettag. From 2009-2015, there were 16 workshops and 231 delegates trained with special emphasis on neuroendoscopic and spine physical simulator training.

NETS Short-Term Neurosurgery Skills Training (2002-2022)
2 Weeks short-term trainees: 151
4 Weeks short-term trainees: 145
Total no. of short-term trainees: 296
AIIMS residents (Neurosurgery, ENT, General surgery, GI surgery, Maxillo facial surgery, Orthopedics, Plastic surgery): 460
Total no. of training sessions: 14377

NETS Workshops (2006-2022)
Total no. of workshops: 101
Total no. of delegates: 1119

WFNS Neuroanatomy Workshop (2018)
Total no. of delegates: 75

Indo-German Workshops (2010-2015)
Total no. of workshops: 16
Total no. of delegates: 248

MIT-HARVARD-IITD Workshop (2013)
Total no. of delegates: 34

Int. Neurovascon Workshop (2011)
Total no. of delegates: 38

Indo-Japan Workshops (2017-2018)
Total no. of workshops: 3
Total no. of delegates: 167

NESI Workshop (2016)
Total no. of delegates: 28

WFNS Neuroendoscopy Workshop (2015)
Total no. of delegates: 112

ISPN Craniofacial Workshop (2012)
Total no. of delegates: 15

WFNS Skull Base Workshop (2007)
Total no. of delegates: 41

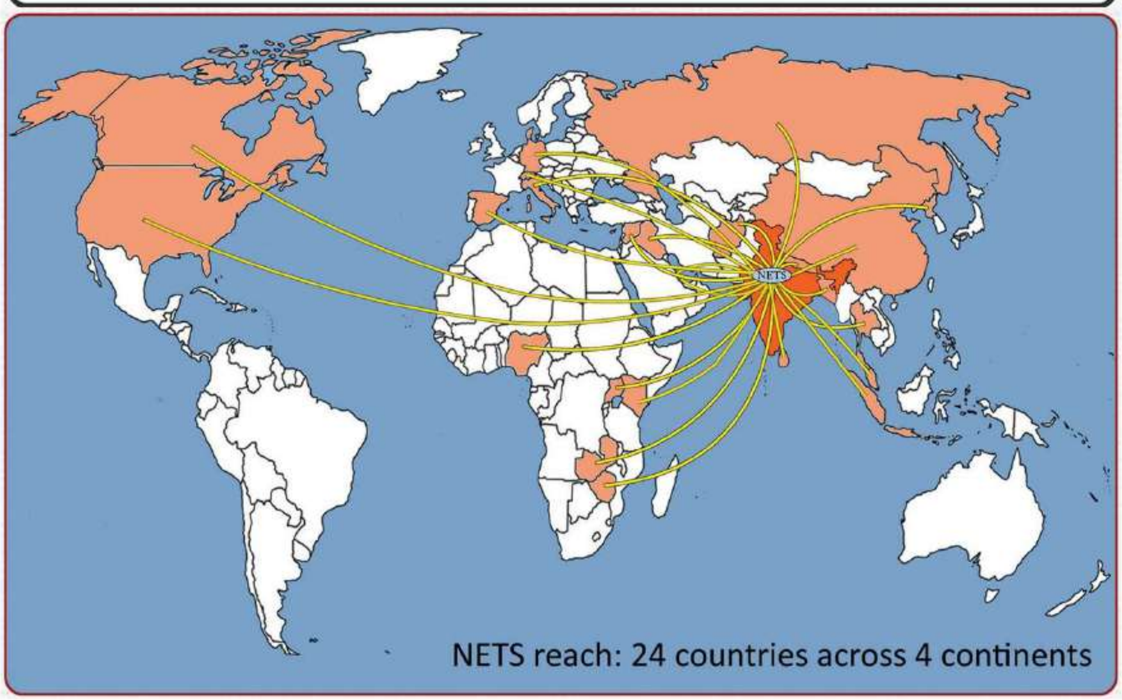


Figure 6. Impact and outreach of NETS-NSTF short-term training program.

Indo-US Collaboration:

NETS-NSTF was central to 3 Indo-US collaboration workshops held at Coimbatore, Hyderabad and Chennai involving American and Indian Professional Neurosurgery Societies-Congress of Neurological Surgeons (CNS) and Neurological Society of India (NSI) respectively with dignitaries from all around the world. The workshops involved virtual reality and physical simulator-based training and evaluation.

Indo-Japan Collaboration:
Three Indo-Japan collaboration workshops were held at our lab with luminaries such as Prof. Kenji Ohata from the University of Osaka, Japan and involving the Ministry of Economy, Trade & Industry, Govt. of Japan. The workshops had special focus on 3D neuroendoscopic anatomy, cadaveric skull base demonstrations, neurovascular simulator training and assessment with 3 modules, 10 stations, 40 delegates, and 4 Japanese faculty.

Philosophy of NETS-NSTF

The development and practice of any skill evolves the subject as a whole and converts what was perceived as an innate God given Art to a meticulous science with a structured modality of practice. This practice is difficult in medicine and neurosurgery in particular as patients cannot be treated as experimental specimens for practice without any previous training. Hands-on, open-source, low-cost, validated, structured training modules such as the ones developed and employed in the NETS-NSTF, AIIMS, New Delhi, if made widespread shall reduce the number of cadaver and animal models needed for training. Furthermore, automated, objective AI based evaluation with expert oversight will ensure to flatten the learning curve and help rapidly develop anatomic orientation and operative intelligence. Ad-hoc training at centers of excellence such as ours with formative and summative assessment shall provide a boost to the development of acumen and skills. This philosophy if integrated in neurosurgical curriculum worldwide with national and international collaborations shall bolster future neurosurgical training.

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Conflicts of interest

The authors declares that they do not have conflict of interest.

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Ethics Approval

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