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EDITORIAL

Hybrid operating theatre in neurosurgery: the future of neurosurgery

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Introduction

Neurosurgery has evolved through successive waves of technological innovation spanning more than a century. The introduction of the surgical microscope in the 1960s revolutionised the precision of intracranial dissection; the development of stereotactic systems provided three-dimensional spatial targeting; the emergence of neuronavigation enabled real-time intraoperative guidance; and the endovascular revolution introduced catheter-based techniques capable of treating vascular pathologies that had previously been approached only through open surgery. Each of these advances redefined the boundaries of treatable neurological disease and demanded new skills, new infrastructure, and new models of multidisciplinary collaboration.

In recent years, arguably the most consequential development in this trajectory has been the emergence of the hybrid operating theatre—an integrated surgical environment that combines the capabilities of a conventional neurosurgical operating room with advanced intraoperative imaging systems and dedicated endovascular infrastructure (1). The hybrid OT enables open microsurgical procedures, diagnostic cerebral angiography, and therapeutic endovascular interventions to be performed within the same operative suite, without the need for patient transfer between locations.

Traditionally, these two domains—open neurosurgery and endovascular neurointervention—occupied separate physical environments: the conventional operating theatre and the angiography suite. This geographic separation introduced workflow inefficiencies, procedural delays, and patient safety risks, particularly in critically ill patients with acute cerebrovascular disease who required sequential or combined treatment strategies (2). The hybrid OT dissolves this boundary entirely, enabling a new paradigm of integrated neurovascular care.

The significance of this development extends beyond its immediate clinical utility. As neurovascular disease management has become increasingly multimodal—combining open surgery, endovascular intervention, radiosurgery, and medical therapy in individualised treatment strategies—the hybrid operating theatre has emerged as the physical embodiment of this multimodality. It functions not merely as a room equipped with extra technology, but as the architectural expression of a new philosophy of neurosurgical practice (3).

This article examines the hybrid operating theatre from multiple perspectives: its definition and technical composition, its established clinical applications, its documented advantages, the challenges it presents, and its emerging role in the evolution of neurosurgical practice. Particular attention is devoted to the implications of hybrid OT development within the Indian public healthcare system, where the recent establishment of a first-of-its-kind government-sector facility at Government Kilpauk Medical College, Chennai, offers important lessons about feasibility, adaptability, and equity in neurosurgical care delivery.

Definition and technical architecture of the hybrid operating theatre

A hybrid operating theatre is a purpose-built surgical environment that integrates the infrastructure of a conventional operating room with advanced intraoperative imaging and endovascular capabilities, allowing both open surgical and image-guided interventional procedures to be performed within the same suite and during the same operative session (4, 5).

In neurosurgery, the essential components of a hybrid OT include: a fully equipped neurosurgical operating room with compatible operating table and headframe systems; advanced fixed or ceiling-mounted angiographic imaging systems, most commonly a biplane or single-plane digital subtraction angiography (DSA) unit with flat-panel detectors; anaesthesia and critical care infrastructure comparable to a standard neuro-intensive care environment; and strict sterility standards and radiation safety provisions required for open surgery under fluoroscopic guidance (6).

The defining operational feature of the hybrid OT is its ability to generate real-time, high-resolution angiographic images during an active surgical session without interrupting the sterile field or requiring patient movement (7). This imaging capability allows immediate verification of surgical or endovascular outcomes—such as confirmation of complete aneurysm obliteration, assessment of residual arteriovenous shunting, or verification of vessel patency following bypass surgery—within the same operative environment in which the intervention was performed.

From an engineering standpoint, integrating advanced imaging into a surgical theatre requires careful architectural planning, including radiation shielding of walls, floors, and ceilings; cable management systems; ceiling suspension or floor-mounted robotic arm systems for the imaging C-arm; adequate floor-loading specifications; and appropriate room dimensions to accommodate both the imaging equipment and the operating team simultaneously (5). Facility design guidelines emphasise the importance of multidisciplinary planning teams—including neurosurgeons, neurointerventionists, anaesthesiologists, radiation physicists, and architects—during the design phase.

Clinical applications of hybrid operating theatres in neurosurgery

Cerebrovascular surgery

The most established and impactful application of hybrid operating theatres is in the management of complex cerebrovascular disease, encompassing intracranial aneurysms, brain arteriovenous malformations (AVMs), cavernous sinus fistulas, and occlusive cerebrovascular disease (3, 8). In aneurysm surgery, intraoperative DSA following microsurgical clip application provides immediate confirmation of complete aneurysm occlusion and parent vessel patency—information that would otherwise require postoperative imaging and, if residual pathology is detected, potentially a second procedure or reoperation.

Studies have demonstrated that intraoperative angiography following aneurysm clipping identifies clip misplacement or residual neck filling in approximately 5–19% of cases, enabling immediate revision during the same operative session (2, 4). For AVM surgery, real-time angiographic assessment following microsurgical resection allows detection of residual nidus or early venous drainage, guiding complete resection and reducing the risk of postoperative haemorrhage.

Endovascular neurointervention

Hybrid operating theatres function as fully equipped endovascular suites, capable of supporting the complete range of interventional neuroradiology procedures, including diagnostic cerebral angiography, aneurysm coiling, stent-assisted coiling, flow diversion, mechanical thrombectomy for acute ischaemic stroke, and embolisation of vascular malformations and hypervascular tumours (9, 10). Performing these procedures within a surgical environment provides the critical advantage of immediate access to open neurosurgical rescue in the event of a catastrophic procedural complication, such as aneurysm perforation or vessel rupture during endovascular coiling.

Combined open–endovascular (hybrid) procedures

The defining capability of the hybrid OT—and the origin of its name—lies in facilitating combined open and endovascular strategies within the same operative session (5, 8). Clinical examples include: preoperative or intraoperative embolisation of AVMs to reduce intraoperative blood loss followed immediately by microsurgical resection; combined clipping and coiling strategies for complex or giant aneurysms not amenable to either modality alone; intraoperative endovascular balloon occlusion of the parent vessel for proximal control during complex aneurysm dissection; and concurrent bypass surgery with endovascular flow diversion for fusiform or giant aneurysms.

Skull base and tumour surgery

In skull base surgery, hybrid operating theatres enable intraoperative vascular assessment during resection of highly vascular tumours or lesions involving critical neurovascular structures, including paragangliomas, meningiomas encasing the cavernous sinus, and hypervascular metastases (11). Intraoperative angiography assists in identifying vascular encasement, confirming arterial preservation, and detecting inadvertent vascular compromise that may not be apparent on direct surgical inspection.

Trauma and emergency neurovascular procedures

In selected cases of neurovascular trauma—including traumatic intracranial pseudoaneurysms, carotid–cavernous fistulas, and traumatic arteriovenous fistulas—hybrid operating theatres enable combined diagnosis and treatment of vascular injuries in a single environment (12). The ability to transition from open surgical decompression to endovascular control, or vice versa, is particularly valuable in polytrauma patients where haemorrhage control may require simultaneous open and endovascular strategies.

Advantages of the hybrid operating theatre

Enhanced intraoperative decision-making

The most transformative advantage of the hybrid OT is the elimination of decision-making latency—the interval between performing an intervention and obtaining objective evidence of its outcome (2). In conventional workflows, this latency may extend hours to days, during which a patient with residual pathology may be at risk for haemorrhage, ischaemia, or clinical deterioration. Real-time intraoperative angiography collapses this interval to minutes, enabling surgeons to identify and correct suboptimal outcomes during the same operative session.

Enhanced patient safety

Patient transfer between procedural areas carries inherent risks, including haemodynamic instability during transport, loss of airway control, hypothermia, and contamination of sterile fields (2). Hybrid operating theatres eliminate these risks by enabling all diagnostic and therapeutic steps to be performed under continuous anaesthesia, monitoring, and sterile conditions within a single environment. This is particularly critical for haemodynamically unstable patients in whom any interruption of monitoring may be life-threatening.

Procedural flexibility

The hybrid OT provides unmatched procedural flexibility, allowing surgeons to modify treatment strategies dynamically in response to intraoperative findings (5, 8). A procedure planned as purely microsurgical may incorporate an endovascular component if intraoperative angiography reveals residual pathology; conversely, a planned endovascular procedure may be escalated to open surgery if a complication requires direct surgical management. This adaptability is fundamental to the management of complex neurovascular lesions whose optimal treatment strategy cannot always be fully predetermined.

Training and education

In academic and teaching institutions, hybrid operating theatres serve as uniquely valuable training platforms. Neurosurgery residents, neurointerventional fellows, anaesthesiologists, scrub nurses, and radiographers gain simultaneous exposure to open surgical and endovascular techniques within a single integrated environment (13, 14). This integrated training model accelerates the development of multimodal competency and is particularly valuable for producing the next generation of neurovascular surgeons capable of navigating the full spectrum of cerebrovascular management strategies.

Workflow efficiency and resource optimisation

By consolidating multiple procedural capabilities into a single suite, hybrid operating theatres reduce procedural duplication, eliminate inter-departmental transfers, and optimise utilisation of anaesthesia, nursing, and technical resources (1). In healthcare systems with resource constraints, this consolidation may represent a meaningful long-term efficiency advantage, particularly when the hybrid OT is used to replace or supplement standalone angiography suites that would otherwise require separate staffing and maintenance.

Challenges and operational considerations

Despite their significant advantages, hybrid operating theatres present several important challenges. The capital cost of establishing a hybrid OT—including acquisition of a high-quality fixed DSA system, architectural modification for radiation shielding, specialised operating tables compatible with fluoroscopy, and ancillary infrastructure—represents a substantial financial investment that may range from several hundred thousand to several million US dollars, depending on equipment specifications and facility requirements.

Radiation safety represents another critical consideration. The routine use of intraoperative fluoroscopy and DSA exposes surgical staff—including neurosurgeons, anaesthesiologists, scrub nurses, and technicians—to ionising radiation, necessitating comprehensive radiation protection protocols, exposure monitoring, personal dosimetry, lead shielding, and institutional radiation safety training programmes (6).

Operational sustainability requires ongoing multidisciplinary collaboration, scheduling coordination between neurosurgical and neurointerventional teams, and investment in staff training. Without adequate procedural volume and institutional commitment, hybrid OTs risk underutilisation, which may compromise their economic justification.

In public-sector institutions in low- and middle-income countries, these challenges are amplified by budgetary constraints, procurement bureaucracy, maintenance limitations, and difficulties in attracting and retaining specialists with hybrid procedural expertise. Structured collaborative models—such as scheduled visiting neurointerventionist arrangements during the early phase of program development—may represent a pragmatic initial strategy for building capacity while training institutional personnel.

The Indian public-sector experience: a first-of-its-kind initiative

The establishment of a hybrid operating theatre at Government Kilpauk Medical College Hospital, Chennai, marked a landmark development in Indian public healthcare. Prior to this initiative, patients requiring diagnostic cerebral angiography or endovascular neurointervention at this institution were routinely referred to external centres—predominantly private hospitals—resulting in procedural delays, substantial additional costs for patients of limited economic means, and attrition of patients who could not afford or access the required care.

The hybrid OT at Government Kilpauk Medical College was established with support from the Japan International Cooperation Agency (JICA) and the Tamil Nadu Health Systems Project (TNHSP), representing an important model of international and state-level collaboration in strengthening public-sector tertiary neurosurgical infrastructure. The facility integrated DSA imaging capability within a fully functional neurosurgical operating environment, enabling diagnostic and therapeutic endovascular procedures to be performed without patient transfer.

During the initial phase of program development, endovascular neurointervention services were initiated through a structured elective model involving scheduled visits by an experienced external neurointerventionist collaborating with the institutional neurosurgery and anaesthesia teams. This approach allowed safe program initiation while institutional staff gained supervised exposure to endovascular techniques. During this early phase, 13 patients underwent endovascular procedures within the hybrid OT, including diagnostic cerebral angiography and therapeutic interventions such as endovascular aneurysm coiling and stent-assisted coiling. All procedures were completed successfully, with no major periprocedural complications and no in-hospital mortality.

Although limited in scale, this initial experience demonstrates several important principles: that hybrid OT infrastructure can be successfully implemented within a government medical college; that structured collaborative models can enable safe program initiation in the absence of pre-existing in-house endovascular expertise; and that public-sector hybrid OTs can deliver outcomes comparable to those reported from private-sector facilities. Beyond these clinical insights, the public-sector hybrid OT at Government Kilpauk Medical College serves as a training platform for neurosurgery residents and postgraduate anaesthesiology trainees, supporting the development of the next generation of neurovascular specialists within the public healthcare system.

The scalability of this model—to other government medical colleges across Tamil Nadu and India more broadly—represents an important priority for expanding equitable access to advanced neurovascular care. With appropriate institutional support, capacity building, and sustainable operational planning, hybrid OT–based neurovascular programs have the potential to transform public-sector neurosurgical practice across the country.

Future directions: the hybrid OT as a digital surgical ecosystem

Cone-beam CT integration

Contemporary hybrid imaging platforms increasingly incorporate cone-beam computed tomography (CBCT) capability alongside conventional DSA, enabling volumetric three-dimensional imaging of the brain, vessels, and implanted devices within the operative suite (2). CBCT allows intraoperative detection of haemorrhage, ischaemia, or device misplacement that may not be evident on two-dimensional angiographic projections, further enhancing the precision of intraoperative assessment.

Robotic endovascular systems

Robotic-assisted endovascular systems capable of remote catheter manipulation are entering clinical practice and are expected to integrate naturally within hybrid OT environments (15). These systems offer the potential for greater procedural precision, tremor elimination, and—in the longer term—remote or teleoperated neurointervention for underserved regions without local specialist access.

Augmented reality surgical navigation

The integration of augmented reality (AR) navigation platforms within hybrid OTs allows real-time overlay of preoperative imaging, vessel anatomy, and intraoperative DSA data onto the operative field, enhancing spatial orientation and procedural precision during open cerebrovascular procedures (3). As AR technology matures, its application within hybrid environments is expected to expand significantly.

Artificial intelligence–assisted imaging analysis

Artificial intelligence (AI) algorithms capable of automated angiographic analysis—including vessel segmentation, aneurysm detection, AVM nidus delineation, and perfusion assessment—are under active development and are expected to function as real-time decision-support tools within hybrid OTs (15). AI-assisted imaging has the potential to reduce interpretive variability, accelerate intraoperative decision-making, and provide quantitative outcome metrics that support procedural quality assurance.

Towards the integrated digital surgical ecosystem

Taken together, these technological developments point towards an evolution of the hybrid OT from a room combining two procedural modalities into a fully integrated digital surgical ecosystem—a dynamic operative environment in which real-time imaging, robotics, AI-assisted analysis, and multimodal navigation converge to support unprecedented levels of surgical precision and intraoperative intelligence (3, 15). This vision positions the hybrid operating theatre not as a specialised niche facility but as the central infrastructure of modern, precision-guided neurosurgical practice.

Conclusion

Hybrid operating theatres represent a fundamental evolution in neurosurgical practice—one that transcends mere technological augmentation to reflect a new philosophy of integrated, multimodal, precision-guided cerebrovascular care. By enabling open microsurgical and endovascular techniques to function as complementary components of a unified treatment strategy within a single operative environment, hybrid OTs have expanded the therapeutic possibilities available to neurosurgeons managing complex neurovascular disease, enhanced patient safety, and improved the precision of intraoperative decision-making.

The early public-sector experience from Government Kilpauk Medical College, Chennai, demonstrates that these benefits are not limited to elite private institutions in high-income countries. With appropriate institutional support, collaborative operational models, and strategic investment, hybrid OT infrastructure can be successfully implemented within government medical colleges—delivering advanced neurovascular care to patient populations who have historically lacked access to such services, while simultaneously serving as training platforms for the next generation of neurosurgeons and neurointerventionists.

As emerging technologies—including robotic endovascular systems, augmented reality navigation, cone-beam CT, and AI-assisted imaging analysis—integrate progressively into hybrid operative environments, the hybrid OT is positioned to evolve into the defining infrastructure of twenty-first century neurosurgery. For complex neurovascular disease, where procedural completeness, vessel preservation, and rapid complication recognition determine long-term neurological outcomes, hybrid capability is no longer a luxury. It is becoming the standard of care.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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