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Preparation of the Interventional Suite for Treatment of Neurovascular Diseases and Emergencies

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The current scope of endovascular technology and associated clinical applications has led to the need to modify the angiography suite to have more of an operating room type of environment so as to perform the full range of elective and emergent neurovascular procedures. This conversion is a complex task given the wide spectrum of disorders, equipment, and personnel involved. As the "captain of the ship," the neurointerventionist must have a good understanding of the pathophysiology of the patient's disease and be able to use the skills of all team members to provide optimal patient care. This article provides an overview of the physiology and pharmacology encountered in the neurointerventional suite and the necessary room or equipment setup and personnel roles required to treat neurovascular disease successfully. Patients presenting to the neurointerventional suite may need elective (eg, unruptured aneurysm or arteriovenous malformation [AVM], carotid or intracranial stenosis, tumor embolization, radiosurgery, angiography, petrosal sinus sampling) or emergent (eg, hemorrhage caused by ruptured aneurysm or AVM, vasospasm, thromboembolic stroke, vein of Galen malformations, epistaxis) care (Table 1).

Before the procedure begins

Many patients treated by endovascular techniques are poor surgical candidates because of multiple medical comorbidities that require special consideration during preprocedural evaluation. A thorough review of systems should be performed to identify cardiopulmonary dysfunction, any abnormality that might increase the risk of anesthesia, renal disease, peripheral vascular disease that might affect vascular access, recent fever or infections that might limit the use of implanted devices, hematologic disorders that might affect hemostasis, and contrast allergies. Patients with intracranial hemorrhage (ICH) must be evaluated for hydrocephalus, because it is preferable to perform procedures like placement of a ventriculostomy before using the anticoagulants that are needed during endovascular procedures. The neurologic examination, when possible, should document any preexisting deficits and should evaluate mental status as well as cranial nerve, motor, sensory, and cerebellar function. Laboratory analysis, including a complete blood cell count as well as electrolyte, blood urea nitrogen, and creatinine levels, should be obtained. Informed consent for an endovascular procedure includes a thorough discussion of the risks and benefits of the planned procedure, the potential for surgical intervention (ventriculostomy, carotid endarterectomy, or craniotomy) in the face of a complication, and alternative therapies. A discussion between the neurointerventionist and the treatment team (nursing staff, technical staff, anesthesia staff, and, if available, the neurophysiologist) regarding the patient's condition and the planned procedures allows for preparation of the proper pharmacologic agents and endovascular devices. The decision to use general

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Table 1
Neurovascular diseases within the neurointerventional suite

Condition	Treatment goal/devices	Potential complications/need for emergent intervention
Aneurysm	Detachable coils, intracranial stents, liquid embolic agents, balloon occlusion	SAH with hydrocephalus: ICP control Procedure-related vascular rupture: complete the embolization, ventriculostomy, control BP, reverse heparin Thromboembolic event: antiplatelet agents, thrombolysis, angioplasty/stent
Thrombo-occlusive disease/stroke intervention	Thrombolytic agents, angioplasty balloons, mechanical thrombolytic devices, intracranial stents	Cerebral ischemia: increase MAP and oxygenation, anticoagulate Vessel perforation: occlude/stent bleeding site, ventriculostomy, craniotomy
Vascular malformations	Embolic agents (NBCA, coils, PVA, liquid agents) radiosurgical angiography, surgical exposure for venous access (SOV cutdown)	Hemorrhage: ICP control, ventriculostomy, decrease MAP Thromboembolic events
Carotid stenosis	Angioplasty balloons, stents	Prepare for complications related to comorbidities, including cardiac disease and peripheral vascular disease Angioplasty-induced bradycardia: atropine, fluids, vasopressors or pacing device if necessary
Medically intractable vasospasm	Angioplasty balloons, intra-arterial vasodilatation agents	Prevent further ischemia: increase MAP, barbiturates, CSF drainage Vessel perforation (see above)
Tumors/epistaxis	Embolic agents (coils, liquid agents, PVA)	Thromboembolic event: attempt to identify and avoid all potential anastomoses Tumor swelling: steroids, be ready to resect tumor if necessary

Abbreviations: BP, blood pressure; CSF, cerebrospinal fluid; ICP, intracranial pressure; MAP, mean arterial pressure; NBCA, N-butyl cyanoacrylate; PVA, polyvinyl alcohol; SAH, subarachnoid hemorrhage; SOV, superior ophthalmic vein.

anesthesia on noncomatose patients in the neurointerventional suite remains controversial, because the advantages of a real-time neurologic assessment in the awake patient must be weighed against the added control over patient cooperation and physiologic variables in the anesthetized patient.

Developing the surgical plan

When possible, the neurointerventionist should develop a comprehensive plan of attack so that each member of the team understands his or her role and is ready to perform his or her duties as required. A preoperative strategy should include contingency plans to use in the case of a complication so that the team can quickly attempt to stabilize the patient. The technical staff should attempt to have potentially necessary endovascular devices readily available so as to avoid delays in the case of an emergency. The nursing staff must be aware of any critical care issues that require their attention, including monitoring vital signs, respiratory status, and intracranial pressure (ICP). This includes preparing medications that may be needed during the procedure. The anesthesia staff should be aware of the treatment goals and should be prepared to intervene as needed, such as to administer protamine to reverse the effect of heparin in the face of a hemorrhagic complication.

The key to a successful surgical plan is establishing a clear treatment goal leading to a safe and effective end result. The neurointerventionist may be tempted to stray from this goal to produce a better angiographic result, but this may compromise the patient's outcome with no additional clinical benefit. One example is intracranial

angioplasty and stenting for atherosclerotic disease. Poiseuille's law states that flow through a cylindric pipe is directly proportional to the radius to the fourth power. This suggests that the slightest increase in vessel diameter might produce a clinically significant improvement in blood flow even if the angiogram documents some degree of residual stenosis. This same concept should guide the surgical plan during coiling of a broad-based ruptured aneurysm in a poor-grade subarachnoid hemorrhage (SAH) patient. It may be safer and more efficient to coil only the dome of the aneurysm to temporarily protect against rerupture until the patient recovers and can better tolerate a longer and more definitive stent-assisted coiling procedure or surgical procedure. The rapid expansion of endovascular techniques and technology is not an indication for their immediate use. New techniques and devices must be closely scrutinized to ensure that their use adds a clinical benefit.

Physiology and pharmacology

The neurointerventionist should attempt to understand the patient's underlying disease state before beginning treatment. The basic concepts of cerebral physiology are paramount to appropriate preprocedural evaluation and management. The brain constitutes only 2% of body weight but receives almost 15% of cardiac output. This disproportionate amount of blood flow to the brain is necessary to meet the high rate of oxygen metabolism (cerebral metabolic rate of oxygen [$CMRO_2$] = 3.5 mL of oxygen per minute per 100 g of brain tissue) [1]. Cerebral blood flow (CBF) averages 50 mL per 100 g/min, and when CBF falls below 10 mL per 100 g/min, irreversible neuronal cell death occurs [2]. CBF is autoregulated by a dynamic cerebrovascular resistance mechanism that maintains CBF over a systemic perfusion pressure of 50 to 150 mm Hg [3]. Blood pressure (BP), oxygen/carbon dioxide tensions, and temperature affect CBF, and these variables can be manipulated to increase the brain's ischemic tolerance. Every 1–mm Hg change in partial pressure of carbon dioxide (P_{CO_2}), when P_{CO_2} is between 20 and 80 mm Hg, linearly alters the rate of CBF by 1 mL per 100 g. In the face of ischemia, this mechanism causes vasodilatation, thus augmenting flow to oxygen-deprived brain. Profound hypothermia (<17°C) reduces $CMRO_2$ to 8% of normal and subsequently decreases CBF. These concepts can be used not only to improve ischemic tolerance in the brain but to reduce ICP.

ICP is determined by the presence of brain tissue (84% or 1100 mL), cerebrospinal fluid (CSF, 12% or 150 mL), and blood volume (4% or 50 mL) within the confines of the fixed intracranial vault [4]. ICP is maintained within a normal range when the volume of one component increases so long as a compensatory decrease in the other components occurs. When the compensation mechanisms fail and ICP increases, the brain attempts to maintain adequate cerebral perfusion pressure (CPP = mean arterial pressure [MAP] – ICP) by driving up systemic BP. Although many devices exist to monitor ICP (eg, epidural or subdural transducer lead, intraparenchymal monitor), a ventriculostomy catheter provides reliable ICP readings and treatment of elevated ICP with CSF drainage. Intracranial hypertension can be treated in the neurointerventional suite with CSF drainage, mild hyperventilation, and pharmacologic agents. Reduction of brain interstitial fluid with mannitol (an osmotic diuretic) or Lasix (a loop diuretic) provides rapid but short-term ICP control. Barbiturates are a powerful tool to reduce ICP and prolong cerebral ischemic tolerance by reducing $CMRO_2$ to 50% of normal and decreasing cerebral blood volume by vasoconstriction (Table 2).

Although a nurse anesthetist or anesthesiologist is present in the neurointerventional suite during the induction and initial administration of general anesthesia, the neurointerventionist should have a basic understanding of the cerebral and systemic effects of the anesthetic agents selected. Isoflurane is the preferred inhaled anesthetic for neurosurgical patients because it causes less vasodilatation or CBF increase than halothane and enflurane while reducing $CMRO_2$ to a greater extent. Sevoflurane provides effects similar to those seen with isoflurane and may have additional cerebral protective effects [5,6]. Certain inhaled agents are avoided when elevated ICP is a concern; these include enflurane (seizure risk), desflurane (increases ICP), and nitrous oxide (increases ICP and CBF). Intravenous anesthetics (eg, propofol, barbiturates) reduce $CMRO_2$ with cerebral vasoconstriction but also cause cardiovascular depression. Benzodiazepines (midazolam) and opioids (fentanyl) can be combined to provide adequate conscious sedation by providing rapid-onset anxiolytic effects and reducing sympathetic responses [7]. Nondepolarizing muscle relaxants (eg, vecuronium) are preferred over succinylcholine (increases ICP and causes hyperkalemia) when rapid-sequence induction is not needed (see Table 2).

Table 2
Pharmacologic agents used in the neurointerventional suite

	Class/mechanism	Dosage, time to effect	Relevant side effects
Diuretics (ICP control)			
Mannitol	Plasma expansion, osmotic diuresis	0.25–1.0-mg/kg bolus Onset: 1–5 minutes Peak: 30–60 minutes	Increases serum osmolarity, hypotension
Furosemide	Loop diuretic	10–20-mg bolus Peak effect: minutes	Hypokalemia
Neuroprotectives/sedatives			
Midazolam (Versed)	Benzodiazepine	1–2-mg initial bolus with total up to 0.1–0.15 mg/kg Onset: 15 minutes Peak: 30 minutes	Respiratory arrest (reverse with flumazenil)
Fentanyl	Narcotic	25–100-μg bolus, repeat as needed Peak: 10–20 minutes	Respiratory arrest (reverse with naloxone)
Propofol (Diprivan)	Hypnotic, mild neuroprotection	5–10-μg/kg/min, titrate to maximum of 50 μg/kg/min Onset: 30–60 seconds	Respiratory depression, hypotension
Pentobarbital	Hypnotic, improved neuroprotection	100-mg bolus, maximum dose of 500 mg Onset: minutes	Respiratory depression, hypotension
Paralytics			
Vecuronium	Nondepolarizing neuromuscular blockade	0.1-mg/kg bolus Onset: 3 minutes Duration: 30 minutes	Prolonged effect in renal failure
Succinylcholine	Depolarizing neuromuscular blockade	1-mg/kg bolus Onset: 30–60 seconds	Hyperkalemia with neuronal damage
Anticoagulants/thrombolytic agents			
Heparin	Inactivates/blocks thrombin, preventing clotting cascade	Dosage is weight based, titrate to goal ACT >250 seconds	Does not lyse formed clot, hemorrhage risk, thrombocytopenia, platelet aggregation
t-PA (Activase)	Fibrinolysis	Intra-arterial dosage is variable	Hemorrhage risk
Integrilin	GPIIb-IIIa receptor block, preventing platelet aggregation	180-μg/kg bolus, then weight-based infusion dosage	Hemorrhage risk, thrombocytopenia
Abciximab (ReoPro)	GPIIb-IIIa receptor block, preventing platelet aggregation	Intravenous bolus of 0.25 mg/kg, then infusion of 10 μg/min Intra-arterial dosage varies	Hemorrhage risk, neutropenia
Clopidogrel (Plavix)	Inhibits ADP-induced platelet aggregation	300-mg oral load, then 75 mg daily with aspirin, 325 mg Peak effect: 5 days	Hemorrhage risk
Bivalirudin	Direct thrombin inhibitor	Dose is variable	Hemorrhage risk

Abbreviations: ACT, activated coagulation time; ADP, adenosine diphosphate; GP, glycoprotein; ICP, intracranial pressure; t-PA, tissue plasminogen activator.
Adapted from PDR.net.

The use of neurophysiologic monitoring is equally controversial to the use of general anesthesia on noncomatose patients. In patients undergoing procedures with general anesthesia, this form of continuous real-time evaluation serves as an early warning detection system compelling the endovascular surgeon to address and treat arterial compromise or injury. Early and rapid intervention or technique adjustment can then be instituted and is believed to translate into improved clinical outcomes. Persistent changes in or the disappearance of electroencephalography, brainstem auditory evoked potential, and somatosensory evoked potential recordings often correlate with development of new neurologic deficits after cerebral vascular procedures. As with open cerebral aneurysm surgery, the impetus for simultaneously using these various neurophysiologic techniques during endovascular treatment of aneurysms stems from the correlation that has been demonstrated between electrophysiologic change and alterations in CBF [8–10]. Circumstances encountered during endovascular treatment of cerebral aneurysms (eg, emboli, parent vessel or aneurysm rupture, vasospasm, temporary occlusion with balloon remodeling) can result in cerebral ischemia, which is easily detectable using neurophysiologic monitoring modalities. Neurophysiologic monitoring has proven to be useful in many potentially adverse situations encountered during endovascular coiling of cerebral aneurysms in the anesthetized patient. Benefits include adding a level of confidence regarding the occlusion time that can be tolerated while the aneurysm is treated by use of the balloon-remodeling technique, providing the interventionist with important physiologic information when aneurysm rupture occurs, recognition of distal embolic events not necessarily observed during the coiling procedure itself, and detection of reduced cerebral perfusion secondary to vasospasm in proximal vessels through which the catheter has been passed.

Designing the ideal neurointerventional suite

Given the wide array of neurovascular disorders treated in the neurointerventional suite, the room space must be efficiently allocated to each team member so as to provide an environment for implementing the coordinated treatment plan. When determining the size and layout of the room, it is important to consider storage area requirements for devices and drugs while minimizing unusable floor space as a result of mobile imaging equipment, doors, and monitoring devices. A clear path must be maintained in the room for movement of anesthesia and neuromonitoring equipment and the largest bed used by the facility. Mobile ceiling-mounted monitors allow visualization of the fluoroscopic and angiographic images as well as the patient's physiologic data from either side of the operating table while reducing floor space needs. Additional monitors are necessary in the control room. Focused lighting for the angiographic table and accessory tables should be available, because many of the devices used during neurointerventional procedures are small and difficult to see in low light settings. Electrical outlets and the various gas and suction connections should be unobstructed and available wherever they would be needed, because extension cords and tubing can also represent a hazard. Uninterruptible power supplies with emergency backup circuits and a dedicated telephone line inside the procedure room are necessary. Special ventilation may be necessary, such as when mixing bone cement. With the increasing complexity of endovascular procedures being performed, often using implanted devices, the importance of performing these procedures in a sterile environment is more apparent. Not only is there presumed to be an advantage to the patient when physicians and other staff use gowns, gloves, hats, and masks, but this same equipment, when combined with eye protection, reduces the risk of exposure of the staff to the patient's body fluids. In most cases, new endovascular suites should be designed to be operating room compatible, and the alterations necessary to achieve this state should be considered when renovating an existing suite. Some of the engineering issues that need to be considered include room air flow; lighting; scrub sink placement; restricted-access corridors; wall, ceiling, and floor materials; and the placement of electrical outlets and gas and suction connections.

Imaging equipment

Diagnostic studies, such as cerebral angiograms, can be obtained using single- or biplane angiography. Advantages of biplane angiography include superior visualization of the anatomy and pathologic findings as well as reduced radiation and contrast doses. Therapeutic procedures, such as aneurysm or AVM embolization, can be performed more efficiently and safely with the use of biplane angiography and fluoroscopy, because different views may be appreciated

simultaneously. For neurointerventional procedures, simultaneous biplane fluoroscopy and road mapping are useful, as is rotational angiography. On new equipment, three-dimensional angiography should be available. Because of the increasing incidence of obesity, patients weighing more than 150 kg are being treated more frequently; thus, the capacity of the angiographic table should be carefully considered. Angiographic tables that can tilt and rotate are helpful for certain studies, such as for imaging the hand during radial artery access.

Twelve- to 13-in image intensifiers are currently the size most commonly installed in new neurointerventional rooms. Image intensifiers used for angiography usually have three to five modes. When using a larger diameter image intensifier in magnification mode, the radiation dose to the patient increases somewhat; it takes more radiation to generate enough light within the image intensifier for it to function properly. This is one of the disadvantages of using larger than necessary image intensifiers. Another disadvantage associated with larger image intensifiers is that it is often more difficult to position the image intensifier close to the patient; steeply angulated views may not be possible, because the image intensifier will collide with the patient or the table. Biplane flat-panel angiographic equipment will likely be available from the major manufacturers soon. Flat-panel technology is currently more expensive than standard image intensifiers. One advantage of flat-panel technology is its greater latitude or dynamic range. In the future, it is likely that the use of flat-panel technology will be associated with lower radiation doses and increased resolution.

It is important to be able to acquire, process, and review the image data quickly and easily. User-friendly image acquisition and processing hardware and software should be a primary consideration when purchasing new angiographic equipment. Consider how easy it is to magnify images, adjust their brightness and contrast (window/level), add or subtract bone detail, view entire runs or save and recall single images, and add or subtract images from different phases of a run. The operators should be able to calibrate the system accurately and quickly to measure vessels or other structures. Postprocedure image storage, recall, and manipulation should also be easy and fast.

The neurointerventional suite, whether new or a renovation of an existing room, is a major investment. This room will likely be used for many years before being updated or replaced. Therefore, it is important that the construction of this room be carefully planned and executed. Not only should the room be designed to accommodate the procedures performed today, but the designers should attempt to determine how else the room might be used during its lifetime.

Function of the neurovascular team during routine and emergent cases

The endovascular management of the following disorders is discussed in greater detail elsewhere in this issue. The discussion below provides a summary of the role that each team member plays before, during, and after the procedure, with emphasis on the neurointerventionist as the captain of the ship responsible for all actions in the neurointerventional suite.

Thrombo-occlusive disease/stroke intervention

For elective stenting and angioplasty procedures to treat carotid, vertebrobasilar, or intracranial lesions, a thorough evaluation of coexistent peripheral vascular and coronary disease should be obtained. General anesthesia and neuromonitoring provide a safe environment for the procedure, although some interventionists prefer the patient be awake, allowing for real-time neurologic assessment and eliminating the risk of general anesthesia. Given the narrow time window for intra-arterial thrombolysis and clot disruption to produce a favorable outcome, the efforts of each team member must be coordinated during an emergent stroke intervention. The patient is placed under general anesthesia with neuromonitoring, when available, without delay. The designated team member gains arterial access while the nursing team and technician prepare the catheters, thrombolytics, or antiplatelets for microcatheter infusion. The anesthesia team and critical care nurse should work on volume expansion and increasing the MAP to improve collateral flow. Patients may be pretreated with an antiplatelet agent and often receive heparin for anticoagulation during the procedure (see Table 2). Given the risk of hemorrhagic complications with these agents, when possible, all anticipated invasive procedures, such as central line placement and Foley catheterization, should be performed before heparinization. For carotid

stenting, premedication with atropine reduces the bradycardic response associated with balloon dilatation of the carotid bulb [11]. Intravenous fluid and vasopressors, such as dopamine or phenylephrine, must be readily available to treat hypotension and thus reduce the risk of myocardial and cerebral ischemia.

Aneurysm

Patients with intracranial aneurysms present to the neurointerventional suite with elective unruptured aneurysms or SAH after aneurysmal rupture requiring emergent treatment. Special considerations present in the latter group include medical comorbidities, such as aspiration pneumonia or myocardial damage, risk of rerupture and vasospasm, and hydrocephalus requiring ventriculostomy. Ventriculostomy should be performed before the interventional procedure not only to allow ICP monitoring and therapy during the case but to avoid placing the catheter after anticoagulants or antiplatelet agents have been administered. General anesthesia is preferred, allowing for BP manipulation (hypotension before aneurysm embolization versus hypertension with thrombo-occlusive complications), better image quality with a motionless patient, ICP management (sedation), and rapid response to intraprocedural complications (eg, barbiturates, ventriculostomy, craniotomy with intraoperative rupture). Neurophysiologic monitoring has proven useful in identifying intraprocedural thromboembolic events and aneurysmal rupture before it is recognized on an angiographic study and is preferred when readily available. The neurointerventionist should be able to view the BP, pulse oximetry, and ICP values while viewing the imaging screens. The anesthesiologist should be ready to deliver protamine, decrease MAP, and administer barbiturates for cerebral protection in case of intraprocedural vessel rupture. The technicians should understand the treatment plan before beginning the procedure so that they may have all needed catheters, coils, stents, or other devices out and ready for immediate use. These individuals must also maintain a log of all devices used during the procedure. The nurses should prepare all necessary drugs, including sedatives, ICP control agents, anticoagulants, antiplatelet agents, and reversal agents (see Table 2). They must ensure that the crash cart is supplied with resuscitation drugs and supplies for emergent surgical airway control or ventriculostomy while monitoring vital signs and access line patency to maintain irrigation and prevent air embolism. After the procedure, patients often receive heparin or antiplatelet agents when high suspicion for a thromboembolic event exists. The BP cap is liberalized slightly over 24 hours before allowing it to increase as part of hypervolemic, hypertensive, and hemodilution therapy for vasospasm.

Vascular malformations (arteriovenous malformations)

In the neurointerventional suite, patients with cerebral AVMs can be classified into those with ICH as the result of rupture versus those who present electively for staged embolization before definitive surgical/radiosurgical treatment or definitive endovascular AVM obliteration. Issues regarding ICP control and use of anticoagulants in patients with ICH caused by AVM rupture are similar to those in patients with aneurysmal SAH as discussed in the previous section. General anesthesia provides a theoretic benefit for most AVM embolization procedures by minimizing patient movement during microcatheterization of multiple pedicles, allowing for tight MAP control and providing cerebral protection in the face of a complication [12]. The physician or technician must prepare embolic agents in a timely fashion so that they have been mixed to the proper consistency when the interventionist is ready to inject them. The anesthesia team is responsible for lowering the MAP to allow for better AVM nidus penetration during embolization. After the procedure, the BP must be kept strictly under control to avoid normal perfusion pressure breakthrough and subsequent hemorrhage.

Cerebral vasospasm

Patients who have failed maximal medical therapy for vasospasm arrive in the neurointerventional suite in a hypertensive state because they have been treated with vasopressors and in a state of hypervolemia because of increased intravenous fluid loads. These patients are often intubated and are receiving some form of cerebral protection with high-dose sedatives or barbiturates. The anesthesia team must maintain the hypertensive and hypervolemic state during the angioplasty procedure. The interventionist and technician prepare the balloon microcatheter

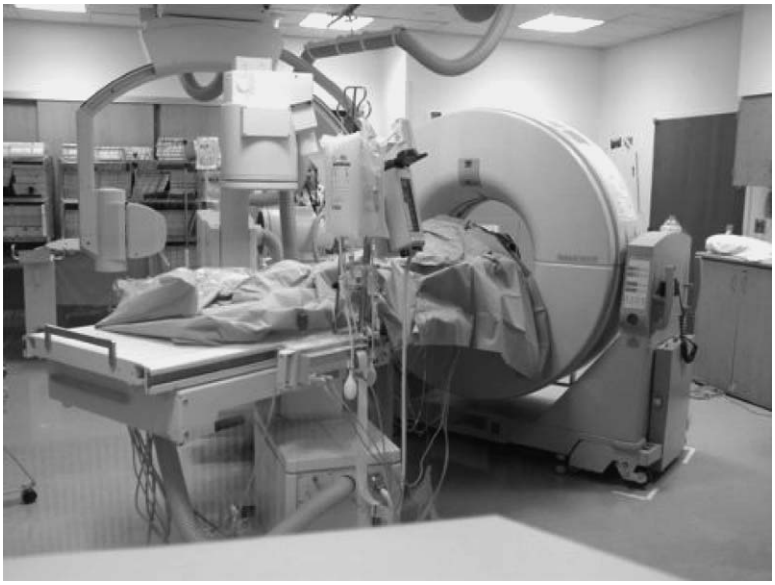

Fig. 1. Use of portable CT scanner in the neurointerventional suite.

while the nurse prepares adequate infusion volumes of intra-arterial papaverine, calcium channel antagonists, or other vasodilators [13,14].

Future directions

With the growth of endovascular technologies and techniques, a larger patient population with a greater diversity of neurovascular disorders may be treated in the neurointerventional suite. The challenge is to train an adequate number of neurointerventionists with a fundamental understanding of the neurovascular patient and the disease process. This should allow the field to grow beyond urban academic medical centers to community and rural medical centers, where time-dependent therapies like stroke intervention may become more successful. In the future, the use of mobile angiography units with telemedicine capabilities may allow the performance of neurointerventional procedures outside the classic neurointerventional suite. Portable CT and MRI scanners may allow for the performance of noninvasive cerebral physiologic studies (eg, Xenon CT blood flow, CT perfusion, MRI diffusion and perfusion) within the neurointerventional suite (Fig. 1). As the number of tools available to the interventionist expands, one must remember the captain of the ship principle. The interventionist must understand how each tool applies to its intended disease and should adequately prepare the neurointerventional team and supervise the coordinated execution of each member's tasks, always being prepared to mobilize emergency plans in the case of a complication.

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