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Anesthesia in PET/MRI. Challenges for the Anesthesiologist: A Narrative Review

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Abstract

Positron emission tomography magnetic resonance imaging (PET/MRI) is an advanced imaging modality that combines metabolic information obtained from PET with anatomical and functional details obtained from MRI. This hybrid imaging technique offers superior spatial and temporal resolutions, making it invaluable in clinical and research settings. This review explores the considerations and strategies for administering anesthesia during PET/MRI procedures. Key aspects include patient immobilization to minimize motion artifacts, optimization of anesthetic agents and techniques, and maintenance of physiological stability throughout the imaging session. The review also addresses specific physiological and anesthetic necessities that may influence or interfere with the effective functioning of the injected radiotracer. Apart from strategies and protocols that can be adapted for the safe delivery of anesthesia, this review highlights vital aspects of radiation safety for anesthesiologists working in PET/MRI.

Keywords
- PET/MRI
- anesthesia
- radiation safety

Introduction

Computed tomography (CT) and magnetic resonance imaging (MRI) are the modalities for morphological and molecular imaging. However, their information is often insufficient for diagnosing, staging, and monitoring tumors and metabolically active lesions.[1] Conversely, positron emission tomography (PET) with fluorine-18 fluorodeoxyglucose (18FFDG) offers functional data on such lesions, lymph node involvement, and distant metastases.[2] Integrating functional, molecular, and morphological imaging enhances diagnostic accuracy for these lesions and metastases. Combining these modalities complements each other, providing a superior diagnostic tool. The integration of PET with MRI, initiated in the mid-1990s, has evolved significantly, addressing safety concerns and improving technology. Despite challenges, such as providing anesthesia in the MRI suite and concerns about radiation from the tracer, this integration has revolutionized the diagnosis and staging of malignancies. In this review, we aim to apprise the anesthesiologists on fundamental physics, safety, and anesthetic considerations associated with positron emission imaging and MRI.

What Is PET?

PET is a noninvasive imaging technique in nuclear medicine. It involves injecting a radiolabeled tracer into the body, allowing it to distribute and accumulate in tissues, and then scanning the body to quantify and observe accumulation patterns. The accumulation is high in tissues with high metabolic activity, such as tumors, rapidly firing areas in the brain, and inflamed tissues.

The positron emitting isotope administered to the patient undergoes β decay, where a proton is converted into a neutron, a positron (the antiparticle of the electron), and a neutrino. The positron travels a short distance before annihilating with an electron. This annihilation produces two

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high-energy photons traveling in opposite directions. Detectors placed at 180 degrees detect these photons, and the radioactivity is localized along a line between the two detectors, known as the line of response.

The most commonly used radionuclides, or tracers, in PET imaging are ^{11}C (half-life of 20 minutes), ^{13}N (half-life of 0–10 minutes), ^{15}O (half-life of 2 minutes), and ^{18}F (half-life of 110 minutes). These isotopes are chosen because carbon, nitrogen, oxygen, and hydrogen are fundamental components of biologically important molecules. However, hydrogen does not have a radioisotope emitting gamma radiation that can be detected externally; it is replaced by fluorine for PET imaging purposes.[3] FDG is produced when protons (nucleus of a hydrogen atom) collide with ^{18}O—a stable isotope of oxygen.[4] The resulting ^{18}F thus obtained undergoes multiple other steps of purification and sterilization, which is finally combined with glucose to yield injectable FDG.

What Is Gamma Radiation?

Gamma rays, being high-frequency ionizing radiations, carry significant energy and can ionize atoms they encounter, including those within the human body. When absorbed by the body, gamma rays have the potential to cause damage to deoxyribonucleic acid (DNA), leading to various detrimental effects. Gamma radiation exposure can lead to damaging effects on DNA, cell membranes, and proteins, ultimately impacting cellular function and integrity.[5]

Anesthesia Concerns in the PET/MRI Suite

PET/MRI suites are usually situated in locations that are away from the main hospital complexes or restricted areas for human movement due to the involvement of radiopharmaceuticals. This renders the area of PET/MRI a remote location from an anesthesia point of view. Details of inevitable challenges faced in remote locations, more so in areas that are away from the operation theaters and intensive care units, were enumerated in a review by Dexter and Wachtel.[6] While anesthetizing in remote locations, anesthesiologists should first become familiar with the physical site, available equipment, and drugs. Preanesthetic evaluation becomes crucial, and it is always good to have trained manpower to assist. It would be good if the anesthesiologists were familiar with anesthetizing patients for MRI. Apart from patient safety being the prime concern for the safe conduct of anesthesia in MR units, the protection of personnel involved in the anesthesia process from radiation-induced harm is also important in combined PET/MRI suite.

PET/MRI Suite Design

A line diagram of the PET/MRI setup in the authors' institution is given in ►**Fig. 1**, depicting the preoperative, injection, and pre- and postprocedure monitoring areas (active patient waiting area). The active patient waiting area has been equipped with an anesthesia machine with a ventilator, crash cart, and patient monitors. Remote cameras enable continuous monitoring of this area from the console room, significantly

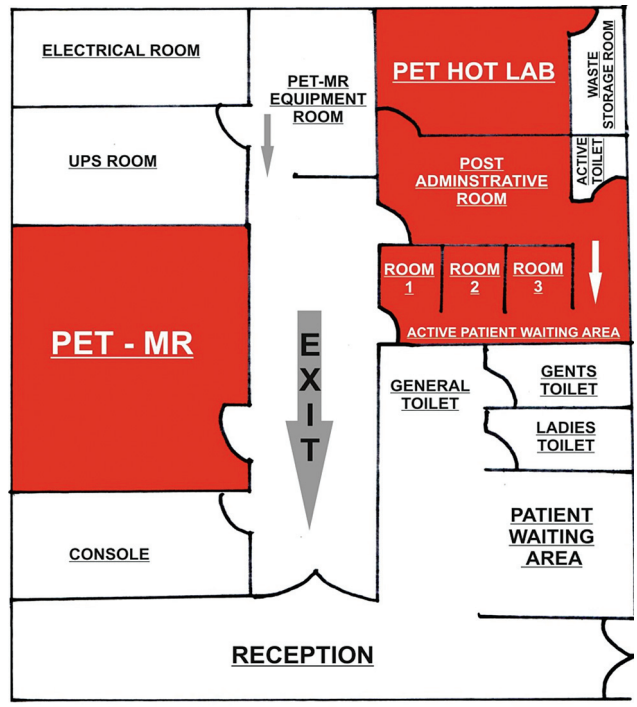

Fig. 1 Line diagram of the positron emission tomography magnetic resonance imaging (PET/MRI) unit layout.

mitigating radiation exposure for health care personnel. Following the tracer injection, patients are observed in the active waiting area. When necessary, they are transferred to the gantry for scanning, and afterward, they return to the active patient waiting area for further monitoring.

Protection of Working Personnel from Radiation

The fundamental principle and guide for protection against any radiation is based on the "ALARA" principle. ALARA stands for "As Low As Reasonably Achievable"; there are three components of the ALARA principle that help reduce the radiation dose received. They are the following:

- *Time:* Limit the amount of time spent near the radiation source. While working near the radioactive source, one should work as quickly as possible and leave the area to reduce the radiation dose.
- *Distance:* Increasing the distance between the radiation source and personnel. The dose rate decreases as the inverse square of the distance; when the distance is doubled, the dose rate decreases by a factor of four.
- *Shielding:* Placement of a barrier between personnel and radiation sources. The type of barrier depends on the type of the radiation source. A barrier should be made of a material that absorbs radiation, such as lead, concrete, or water. This can include personal protective equipment (PPE) such as thyroid shields and lead vests.

Time and distance are the two most important factors among the three. PET procedures often deal with gamma rays, which possess high penetrative power. Gamma rays

Table 1 Dose limits recommended by ICRP[25]

Type of dose limit	Limit on dose from occupational exposure	Limit on dose for public exposure
Effective dose	100 mSv over 5 y (20 mSv/y), with no single year exceeding 50 mSv After a worker declares a pregnancy, the dose to the embryo/fetus should not exceed ~1 mSv during the remainder of the pregnancy	5 mSv over 5 y (1 mSv/y)
Equivalent dose to the lens of the eye	100 mSv over 5 y (20 mSv/y), with no single year exceeding 50 mSv	15 mSv in a year
Equivalent dose to the skin averaged over 1 cm^2 of skin regardless of the area exposed	500 mSv in a year	50 mSv in a year
Equivalent dose to the hands and feet	500 mSv in a year	

Abbreviation: ICRP, International Commission on Radiological Protection, mSv- mili Seivert.

require very thick lead or concrete barriers to prevent them from progressing further. It is impractical to wear thick and heavy lead jackets when exposed to gamma radiation. The only practical solution to minimize the effects of gamma radiation is to limit the duration of exposure and increase the distance from the radiation source.

Constant measurement and analysis of the radiation dose absorbed using personal wearable dosimeters are mandatory for all personnel working in areas of radiation exposure. Two kinds of dosimeters are available for use by personnel working in health care:

- *Thermoluminescent dosimeter (TLD) based personal dosimeters:* Thermoluminescent disks coated with nickel and aluminum. They depict the radiation dose received close to tissue equivalents. Absorbed radiation is periodically assessed externally, typically once a month or every 3 months. We cannot get a real-time assessment.
- *Personal electronic dosimeters:* These are active dosimeters designed to be worn by occupational radiation personnel in planned exposure situations. They display the dose and rate of absorption, and some may have alarms if the set threshold is exceeded. These devices are commonly used in PET/CT and PET/MRI units to instantly note the amount of radiation received along with standard TLD badges.

The safe radiation doses recommended by the International Commission on Radiological Protection are listed in ►**Table 1**. A detailed description of the amount of radiation exposure from the patient who received a tracer injection at various time points and at various distances is given in our previous publication (►**Tables 2** and **3**).[7] The role of distance is very clearly visible. At a distance of 10 cm, the radiation was 45 µSv and drops to 15 µSv at 30 cm. Increasing the distance by just 20 cm decreases the radiation levels by two-thirds. This measurement was for 45 minutes of exposure.

Indications for PET Scans

- *Oncology*: Diagnosis, localization, staging, and assessment of treatment response for all types of malignancies. Preprocedural localizations of hotspots for biopsy.
- *Cardiac*: Preprocedural evaluation before revascularization interventions in coronary disease, assessment of cardiac viability, and differential diagnosis of cardiomyopathies.

Table 2 Radiation dose measurements by personal dosimeter in microsievert (µSv) after FDG injection

Type of scan		Distance from the brain			Distance from the abdomen	
		10 cm	30 cm	100 cm	10 cm	30 cm
Brain PET/MRI ($n = 101$)	Prescan (45 min)	44.4 ± 16.61	14.91 ± 5.42	3.55 ± 1.96	54.83 ± 23.64	25.03 ± 12.01
	Postscan (45 min)	31.1 ± 15.77	9.74 ± 5.27	2.77 ± 1.99	30.33 ± 16.07	13.59 ± 8.44
Whole body PET/MRI ($n = 8$)	Prescan (45 min)	90.35 ± 50.49	25.61 ± 10.1	6.58 ± 3.81	105.74 ± 55.26	42.23 ± 19.97
	Postscan (45 min)	51 ± 27.77	14.97 ± 6.59	4 ± 2.65	48.59 ± 28.9	21.1 ± 12.61

Source: Nagaraj et al.[7]

Table 3 Radiation dose measurements of personnel working in PET/MRI facility

Mean dose in μSv/scan/procedure (no. of patients: 112)					
PET/MRI scan	Anesthesiologist	NM physician	Physicist	Radiographer	Staff nurse
Brain/whole body	4.84 ± 0.33	5.66 ± 2.12	7.43 ± 2.54	3.66 ± 2.12	6.66 ± 2.12

Abbreviations: MRI, magnetic resonance imaging; NM, nuclear medicine; PET, positron emission tomography, μSv - micro Seivert.
Source: Nagaraj et al.[7]

- *Neuropsychiatry:* Localization of epileptic foci, neurodegenerative disorders, and neuroinflammation.[4]
- *Miscellaneous:* Localizing sites in cases of pyrexia of unknown origin, disease assessment in human immunodeficiency virus (HIV), infection/inflammation imaging, and other immunosuppressive disorders.

Not all patients who need an MRI require anesthesia/sedation. A certain subset of patients will need sedation/anesthesia to lie down motionless in the MRI gantry.

Anesthetic Management

Preprocedural Assessment and Patient Preparation

A preprocedural anesthesia check is mandatory for patients scheduled for combined PET with MRI. The majority of patients scheduled for PET with MRI in the authors' center are either children or elderly with malignancies and multiple comorbidities. Patients with comorbidities should be optimized to the best possible physiological conditions. Standard fasting guidelines have to be followed before the procedure. On the day of the procedure, patients have to be reassessed again especially in the case of children with any acute respiratory illness. Valid consent is essential for PET/MRI also. It is the entire team's responsibility to ensure that all MR unsafe materials are removed from the patient before entering the MR suite. Adequate intravenous access is obtained with the aid of EMLA cream, especially in children, before radionuclide injection. Uncooperative children or adult patients might need sedation even for the injection of the radiopharmaceutical, which has to be addressed and planned in advance. It is essential to have good glycemic control before ^{18}F-FDG PET scan because hyperglycemia can cause impaired FDG uptake in tumor because of competition with endogenous blood glucose.[8] Hence, the recommendations as per European and American guidelines to measure the blood glucose concentration prior to FDG PET are followed, and if the level exceeds certain levels, the scans must be rescheduled.[9,10] Although it is best to have blood glucose levels of less than 120 mg%, many centers allow up to 150 mg%. In our institution, cases are postponed only if it is more than 180 to 200 mg%.

Following the injection of FDG, the patient is moved into an isolation room and monitored for 30 to 45 minutes for the drug to assimilate in the target areas. If sedation or anesthesia is provided for the patient, facilities to remotely monitor the patients should be available. It is safe to have a fully equipped crash cart and an anesthesia workstation in the isolation room to combat any emergencies.

Sedation/anesthesia is administered after the uptake phase (usually ~30 minutes) because most of the commonly used anesthetic drugs cause a general reduction in glucose metabolic rate, which is associated with the anesthetic state.[11] Finally, the team has to ensure that the patient has emptied the urinary bladder/urine bag if catheterized or, in case of children, has had their diaper changed before being wheeled into the MR suite since the maximum sequestration of radiation emitting tracer will be in the urine.

Equipment and Safety Concerns in the MR Suite

All the equipment inside the MR suite including the anesthesia workstation should be either MR safe or MR conditional. MR safe equipment can be used safely inside the 5 Gauss line, while the MR conditional equipment should be used beyond the 5 Gauss line. Surface skin burns due to pulse oximeters and electrocardiographic (ECG) electrodes have been reported in the past; however, MR safe pulse oximeters and ECG electrodes are available now. Currently available ECG electrodes are attached as a triangular cluster on the chest close to each other, which ensures a high amplitude signal. The data transmitted are via light rather than an electrical current, rendering the information transmitted more resilient to the electromagnetic effects of the MRI (►**Fig. 2**). A multiparameter monitor with facilities for invasive blood pressure monitoring and anesthetic gas monitoring integrated with a slave monitor in the control room is necessary. Infusion pumps/syringe pumps should be either MR-compatible or housed in an MR-compatible jacket (►**Fig. 3**). Long circuits, facemasks/nasal prongs, and end-tidal CO_2 ($EtCO_2$) extensions should be available. A see-through glass partition between the MR suite and the control room is an essential design in any MR establishment. A camera focusing on the patient inside the MR console with a monitor in the control room is indispensable for capturing any patient movements inside the MR console. Sound mufflers applied to the ears of the patient will improve the effectiveness of sedation. Hypothermia in an airconditioned environment is common; however, active heating is not warranted since MR generates eddy currents in the body and may lead to elevation in temperature. Covering the patient in thick sheets is sufficient to conserve body temperature.

Techniques for Anesthesia

There is no consensus or guideline regarding which technique of anesthesia or sedation is ideal. The technique must be tailored considering the patients' physiological status and familiarity with the anesthesiologist conducting such techniques. In the

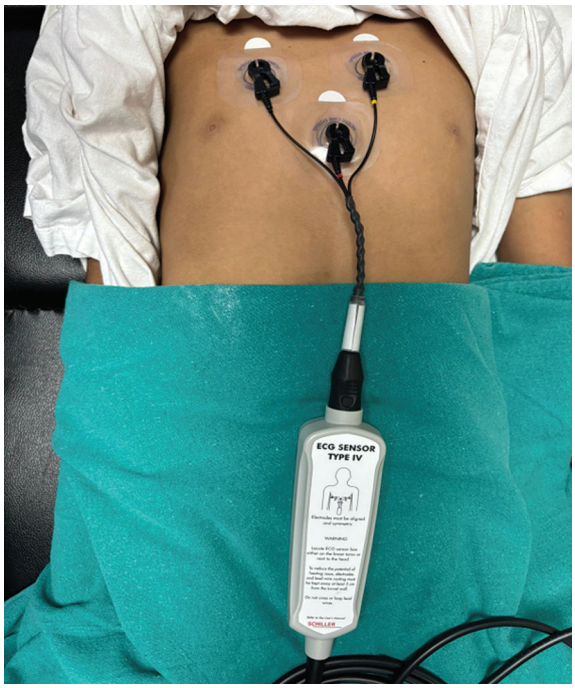

Fig. 2 Electrocardiographic (ECG) electrode placement in positron emission tomography magnetic resonance imaging (PET/MRI).

Fig. 3 Syringe infusion pumps in shielded jacket.

guidelines provided by the Association of Anaesthetists of Great Britain and Ireland, a senior and experienced consultant must be allocated the responsibility of conducting the sedation/anesthetic for MR scans.[12] Exclusive nursing staff and anesthesia technicians (operating department practitioners) should be available to assist the anesthesiologist in performing the procedure and help during emergencies.

The method for sedation/anesthesia depends on the planned duration of the procedure and the patient's physical status. Each center may have a different protocol for integrating the PET and MR images. Both MRI and PET scanning can be planned in one go or MR images are acquired prior to PET and overlapped later. On an average, MR takes 30 to 90 minutes depending on the areas of the body to be scanned and PET takes approximately 15 to 30 minutes for image acquisition. Therefore, the duration of sedation/anesthesia needs to be assessed according to the protocols in respective centers. Most of the time, MRI and PET images are acquired simultaneously. Typically, it takes approximately 30 to 45 minutes for a brain scan and about 1 hour for a whole-body scan.

Sedation: An array of drugs is available to conduct a safe sedation procedure, even for children and elderly patients with multiple comorbidities (►**Table 4**). Sleep deprivation and use of oral triclofos (sedative, hypnotic) are practiced in many centers to sedate children.[13] This technique can be used for sedating children scheduled for MR and PET. Midazolam is favored for anxiety reduction, separation from family, and mild to moderate sedation. Midazolam can be administered orally, intranasally, and intravenously. Oral and intranasal routes facilitate parental separation; however, it may not suffice to complete an entire MR study of 30 to 45 minutes. Some experts suggest combining midazolam with agents such as ketamine or dexmedetomidine is effective in rendering a still patient for the entire duration of the MR study. Another advantage of midazolam is the availability of a specific reversal agent, flumazenil, if required.

Table 4 Commonly used drugs for sedation/deep sedation

Drug	Onset	Duration	Dosage
Midazolam	2–10 min	1–2 h	0.05–0.1 mg/kg IV/IM
Ketamine	1–5 min	30 min–2 h	1–2 mg/kg IV 3–5 mg/kg IM
Propofol	30 s–1 min	5–10 min	0.5–1.5 mg/kg IV bolus 3–6 mg/kg/h infusion
Fentanyl	2–5 min	30–60 min	1–2 μg/kg IV
Dexmedetomidine	5–15 min	10 min–2 h	0.5–1 μg/kg bolus over 10 min, followed by maintenance of 0.2–0.7 μg/kg/h

Abbreviations: IM, intramuscular; IV, intravenous.

Propofol is time tested and the most favored agent for procedural sedation. Strong data support exists for propofol for induction and sedation for children undergoing MR scans. Dosage of 1 to 2 mg/kg for induction and 2 to 5 mg/kg/h has been used and recommended in many studies and reviews in the literature.[14,15] A combination of propofol and ketamine, commonly termed Ketofol, is fast becoming a preferred combination for procedural sedation, even for procedures that involve minor discomfort/pain such as upper gastrointestinal endoscopy and wound dressing changes.[16] Dexmedetomidine, an α2 agonist, has become the new favorite nudging aside propofol for procedural sedation. An intravenous bolus dose of 1 to 2 µg/kg followed by 0.5 to 1 µg/kg/h infusion is the described regimen across various trials.[17,18] Intranasal dexmedetomidine against midazolam has also been described for sedation in the MR unit.[19]

A combination of propofol for rapid induction and dexmedetomidine infusion for continued sedation through the course of the MRI scan in children with excellent success in terms of recovery and quality of MR scan achieved has also been described.[20] In patients deemed not suitable for deep sedation or in those for whom deep sedation was a failed technique, general anesthesia with airway control is the option and is considered safe by some practitioners.[21,22]

General Anesthesia

Failed sedation attempts, extreme anxiety and claustrophobia, critically ill patients, mechanically ventilated patients, very small infants, and patients who are at risk of airway obstruction following sedation will also need general anesthesia with airway control. The principles of general anesthesia remain the same as practiced in the operating rooms; however, the risk of radiation exposure to anesthesiologist exists during a general anesthetic. An induction room to facilitate induction of anesthesia and airway access is a norm in most centers where sedation/anesthesia for MRI is practiced. Airway control can be achieved either with a laryngeal mask airway or endotracheal intubation at the discretion of the attending anesthesiologist. Maintenance of anesthesia can be either volatile anesthetic based or intravenous anesthetics based, with spontaneous or controlled ventilation. The patient can be wheeled back into the induction room for extubation and postoperative recovery.

The main concern in conducting general anesthesia with airway control is the time spent by the anesthesiologist and the assistant near the patient, thereby increasing the absorbed radiation. Key recommendation in general anesthesia cases for PET/MRI is to minimize contact time within 3 feet of an injected patient as much as possible.

Monitoring during PET/MRI Sedation/ Anesthesia

Standard monitors and monitoring used in general anesthesia for MRI are also utilized in the PET/MRI (►**Fig. 4**). An MRI-compatible monitor with a slave monitor in a console room outside the MRI gantry is ideal. ECG, plethysmography, noninvasive blood pressure monitoring, and expired gas $EtCO_2$ are monitored. The electrodes used for ECG monitoring should be MRI compatible. Although expired CO_2 values are not dependable in spontaneously breathing patients, the resulting waves provide an indication of the respiratory pattern in a sedated patient and warn of any apnea or breath-holding spells. The American Society of Anesthesiologists (ASA) Task Force for Procedural Sedation recommends supplemental oxygen to prevent hypoxemia in all sedation procedures.

Postprocedure Discharge Criteria

The ASA Task Force for Procedural Sedation recommends the following after the procedure.[23] Postprocedure, the patient is to be transferred and monitored in a recovery area with adequate staffing until he or she regains near preprocedure consciousness levels and is no longer at an increased risk of cardiopulmonary depression. Oxygenation should be monitored until the patient recovers adequately and the patient is no longer at risk of hypoxemia. Ventilation and circulation should be monitored through noninvasive blood pressure measurements at regular intervals (every 5–15 minutes).

Designed discharge criteria should be observed by trained personnel to minimize central nervous system and cardiovascular depression. The modified Aldrete score seems to cover all the recommendations given by the ASA task force; therefore, it can be used to guide discharge from the recovery postprocedure in the PET/MRI suite also.

Release of Patients to the Community Following Procedure

The release of patients injected with radioactive tracers should be timed, considering the decay and half-life of the agent. The levels of radiation emissions at the time of discharge should be deemed safe for the general population. Aldousari et al,[24] in their work on assessment of external radiation dose rate after ^{18}F-FDG for PET CT procedure, have concluded that patients can be released into the community safely at 2 hours following injection of the tracer. Multiple other studies have suggested that consuming fluids and frequent voiding of urine before discharge will significantly reduce emitted radiation. In the authors' institute, patients are released into the community 150 minutes after ^{18}F-FDG injection.

Summary

Administering anesthesia in a PET/MRI suite combines techniques from standard MR suites with the added consideration of ionizing radiation. To ensure patient stillness, options include sedation or general anesthesia, as discussed in the review. The choice of technique should be informed by factors such as the patient's age, comorbidities, critical condition, and the anesthesiologist's experience. Regardless of the approach taken, it is crucial to maintain a safe distance and limit the time spent near the patient to reduce radiation exposure.

Fig. 4 Positron emission tomography magnetic resonance imaging (PET/MRI) room setup showing the patient gantry, anesthesia machine, monitor, and infusion pumps.

Key points to remember (in anesthetizing patients for PET/MRI)
Blood sugar levels should be below 180 mg/dL before injection of radiopharmaceutical[8]
Propofol/general anesthesia can alter cerebral metabolism and thus the uptake of radiopharmaceutical by the tissue. It may cause difficulty in interpretation of the images. Typically, it is not a concern after 30 minutes postinjection[11]
Always maintain a safe distance from the patient except when close contact is needed for safe conduct of anesthesia. Proper planning of the steps will help
The radiation to the anesthesiologist can be negligible with proper planning and execution[7]

Additionally, since serum glucose levels significantly influence the radionuclide concentration in the areas of interest, preprocedural glucose levels should be carefully considered. With proper planning and execution of anesthetic management, patients can be safely anesthetized without increasing risks for either the patients or the anesthesiologist.

Conflict of Interest
None declared.

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