Chapter 4
Radiation Safety During Surgery for Urolithiasis

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Abbreviations

ALARA	As low as reasonably achievable
BMI	Body mass index
ED	Effective dose
FT	Fluoroscopy time
ICRP	International Commission on Radiological Protection
KUB	Kidney-ureter-bladder
LDCT	Low-dose NCCT
NCCT	Non-contrast CT
PCNL	Percutaneous nephrolithotomy
URS	Ureteroscopy
US	Ultrasonography

Background

On April 26, 1986, the Chernobyl nuclear power plant in Ukraine experienced an accident. On May 11, 2011, the nuclear power plant in Fukushima, Japan, was similarly affected. These accidents resulted in a tremendous fallout of radioactive materials, which greatly influenced the environment, food sources, and local populations for many years. The extended low-dose radiation exposure resulting from these accidents also greatly affected human health. There was an increased incidence of malignancies, including thyroid cancer, leukemia, and breast cancer, among others [1].

Generally, the effects of radiation exposure on human health are referenced as deterministic and/or stochastic. Deterministic effects mean that the severity of certain effects on humans will increase with increasing radiation doses. Below a certain

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exposure level, the “threshold,” the effect is absent. Therefore, the severity of deterministic effects depends on the accumulating radiation dose. There is a threshold for deterministic effects in the skin, lens of the eye, testis, and bone marrow. For example, skin erythema occurs with exposure of 2–5 Gy, hair loss with 2–5 Gy, cataracts with 5 Gy, lethality (whole body) at 3–5 Gy, and fetal abnormalities at 0.1–0.5 Gy. Conversely, stochastic effects have no thresholds. The severity of the threat is independent of the absorbed radiation dose. Thus, the probability of damage (e.g., radiation-induced cancer) is based on the individual’s genetics.

In just a few decades, interventional radiology (IR) has developed as a useful adjunct in the fields of radiology, cardiology, gastroenterology, orthopedic surgery, and urological surgery. It has become a minimally invasive approach to treating various diseases, including both benign and malignant lesions. The great advantages of interventional radiology for patients are that it is less invasive than conventional surgery, including the degree of pain, complications, and cosmetic scarring.

Procedures performed under fluoroscopic guidance for diagnosis and therapy are commonly used in the urological field as well. Endoscopic surgery for treating urolithiasis generally comprises fluoroscopy-guided real-time imaging to add to the safety and success of procedures by avoiding complications and confirming the location of stones, the endoscope, the percutaneous puncture needle, and the anatomical pattern of the urinary tract. The fluoroscopy-guided techniques markedly improve many perisurgical parameters, such as the operation time, blood loss, postsurgical pain, hospital stay, and complication rate.

More sophisticated radiological equipment has contributed to expanding the use of fluoroscopy-guided interventional radiological therapy. During this expansion, however, radiation exposure of patients and medical personnel including the surgeon, assistant surgeon, surgical nurse, and anesthesiologist has increased. Therefore, even if radiation exposure dose is relatively small for medical personnel, urologists must be aware of the risk of the harmful effects of such exposure. Knowledge about the safe use of fluoroscopy may be a less important concern to urologists than to radiologists and cardiologists involved in interventional radiology. Nevertheless, with the worldwide increase in the prevalence of urolithiasis, the influence of radiation exposure must not be ignored. All urologists using fluoroscopy should know about the risk as well as the techniques available to prevent radiation exposure, thereby endeavoring to minimize adverse events following radiation exposure.

The International Commission on Radiological Protection (ICRP) is an international academic organization that developed, maintained, and elaborated on the International System of Radiological Protection used worldwide as the common basis for radiological protection standards, legislation, guidelines, programs, and practice [2]. The System of Radiological Protection is anchored in three fundamental principles according to the ICRP recommendations: justification, protection, and dose limits.

- Principle of justification: Any decision that alters the radiation exposure should do more good than harm.

- Principle of optimization of protection: The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.
- Principle of application of dose limits: The total dose to any individual from regulated sources during planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the ICRP.

Preoperative evaluation and endourological procedures for upper urinary tract stones are mostly performed under fluoroscopy. Patients with urolithiasis and the surgeons and medical staff involved in the management of upper urinary tract stones have numerous opportunities to undergo radiation exposure. Radiation exposure in endourological fields is mainly divided into two parts: (1) the medical exposure for patients and (2) the occupational radiation exposure for surgeons and the medical staff. Although the dose limit for patients' radiation exposure has not been established, the National Council on Radiation Protection and Measurements defined the occupational radiation exposure dose limit as 50 mSV per year [3].

Ionizing radiation exposure is considered a risk factor for malignancies such as thyroid cancer, leukemia, and breast cancer. It is still uncertain, however, how harmful the radiation exposure is in the long term as low-dose irradiation has been extrapolated to estimate the radiation-related cancer risk. Therefore, the linear, non-threshold hypothesis is applied as basic to considering the biological effect of radiation exposure. Some investigators reported that chronic occupational exposure to low levels of ionizing radiation caused an increased frequency of micronuclei in chromosomes, which is a biomarker of chromosomal damage, genome instability, and cancer risk [4]. Also, according to some studies, thyroid cancer increased among Australian orthopedic surgeons as a direct result of constant exposure to low-level ionizing radiation [5]. Protracted low-dose exposure to ionizing radiation has been associated with solid-cancer-related mortality [6]. Occupational radiation to the breast was positively associated with breast cancer risk [7]. Currently, there is great concern about occupational radiation exposure having an influence on the lens of the eye. The ICRP recommends not to exceed a mean eye lens dose of 20 μSv/year.

Here, the issue of long-term low-dose radiation exposure for medical personnel arises. Even if the risk of harmful effects of occupational radiation exposure is relatively small, doses exceeding the standard limits likely carry a small, short-term health risk. The ICRP has recommended the principle of limiting radiation exposure to "as low as reasonably achievable" (ALARA) [8, 9].

Medical radiation protection principles should be applied for both patients and medical staff members involved in imaging (e.g., surgeons, nurses, medical engineers). The general factors that should be addressed to optimize protection against radiation are as follows:

- Time: Radiation time should be minimized for the fluoroscopy duration and the number of X-ray-related photographs obtained.
- Distance: Medical staff should be positioned as far as possible from the X-ray source.
- Shielding: Medical staff should use adequate shielding material—e.g., lead apron, lead glasses, lead glass (radiation-shielding glass), and a shield plate.

It is also important to recognize that the measures taken to reduce the patient's radiation exposure almost always decreases that of the medical staff—but the reverse is not always true [1]. To protect the patients and oneself from radiation exposure—even that as low as possible—physicians must perform the surgery based on these three factors. Hence, the advances needed to create radiation-free techniques for imaging stones are needed. This chapter is focused on preventive methods currently available to minimize radiation exposure for patients and medical personnel.

Radiation Protection for Patients During Diagnosis and Surgery

Radiation exposure during procedures is generally due to either direct or scattered radiation. A major source of radiation exposure for patients during procedures is direct radiation generated in the fluoroscopy field between an X-ray tube and an image intensifier (Fig. 4.1). Direct irradiation provides about 1000 times stronger radiation exposure for patients than scattered radiation. Overall doses of medical exposure are not limited because many patients undergo radiological examinations and treatment, although the amount of radiation exposure per patient depends on their disease. However, decreasing the radiation exposure for patients as much as possible is of great concern according to the ALARA principle. Patients with nephrolithiasis (upper urinary tract stones) suffer radiation exposure from diagnostic, treatment, and follow-up imaging. Children with suspected urolithiasis are a special concern regarding radiation exposure because they may require irradiation over an extended period of time.

Standard diagnostic imaging for nephrolithiasis is mostly performed with non-contrast computed tomography (NCCT). Currently, the effective dose (ED) for NCCT of the abdomen and pelvis is 4.5–5.0 mSv [10]. The use of low-dose NCCT (LDCT) offers the advantage of less radiation exposure for the patients. A meta-analysis of LDCT studies revealed sensitivity and specificity of 96.6% and 94.9%,

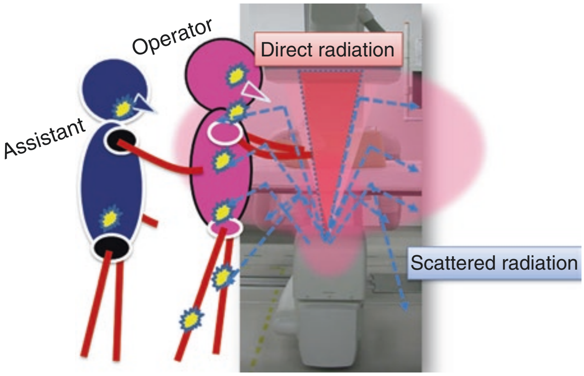

Fig. 4.1 Schema of radiation exposure from direct and scattered radiation for the surgeon and surgical assistant

respectively, for diagnosing urolithiasis, which was comparable to that of NCCT [11]. The mean ED for patients undergoing LDCT was reported at 1.40 mSV in men and 1.97 mSV in women. When body mass index (BMI) was considered, however, the sensitivity and specificity decreased to 50% and 89%, respectively, for those with BMI >30 kg/m^2 [12]. The American Urological Association currently recommends the standard NCCT value over the LDCT value when planning to address stones in obese patients (BMI >30 kg/m^2) [13]. Furthermore, current imaging advances have enabled the development of ultralow-dose iterative reconstruction algorithms, which preserve image quality at low doses, making it possible to evaluate urolithiasis. Ultralow-dose NCCT delivers an ED of <1 mSV, which is a lower ED than that with LDCT [14, 15].

The follow-up of patients on medical expulsive therapy or after procedures for nephrolithiasis have shown that standard imaging studies—plain radiography of the kidney-ureter-bladder (KUB) and ultrasonography (US)—are better modalities than NCCT in terms of radiation exposure and cost. The mean ED for KUB imaging is 0.5–1.0 mSv [16], and the patient is not exposed to any radiation when using US. Current guidelines recommend initial US for children with suspected urolithiasis to avoid being sensitized to ionizing radiation [17].

During procedures for managing nephrolithiasis, including retrograde intrarenal surgery and percutaneous nephrolithotomy (PCNL), almost all patients are exposed to radiation by way of fluoroscopy. The radiation exposure associated with PCNL is generally higher than that with ureteroscopy (URS) for nephrolithiasis because of the prolonged fluoroscopy time (FT). A retrospective study revealed that the mean FT during PCNL was 7.09 ± 4.8 min and the mean ED of patients undergoing PCNL was 8.66 mSV [18]. Furthermore, an increasing number of risk factors—radiation exposure during PCNL, high BMI, high stone burden, and more percutaneous tracts—were significantly associated with an increased radiation ED. Obese patients (BMI >30 kg/m^2) required a more than twofold higher dose than normal weight patients (BMI <25 kg/m^2) (6.49 vs 2.66 mSV, $p < 0.001$) [19].

Various techniques can be used to decrease radiation exposure during PCNL. Air retrograde pyelography with the patient in a prone position can clarify the calyceal anatomy of the puncture site. Consequently, the mean adjusted ED during PCNL was 4.45 mSV for air retrograde pyelography compared with 7.67 mSV for contrast retrograde pyelography. This finding is likely due to the increased density of the contrast medium, leading to automatic adjustment of the C-arm tube and tube voltage (lower tube voltage is needed when air is in the field) [20]. Compared with fluoroscopic guidance to assist PCNL, US guidance reduces radiation exposure and is particularly beneficial for treating obese patients with renal stones [21]. Furthermore, combined US/URS-assisted access for PCNL reduces the mean FT compared with that for conventional PCNL under fluoroscopy-guided access [22].

Generally, radiation exposure of patients with nephrolithiasis is significantly less during URS than during PCNL. One study found a median FT of 46.9 s and a median ED of 1.13 mSV per procedure [23]. Another study found, in an anthropomorphic adult phantom, that during PCNL the mean ED rate (mSV/s) was significantly increased during URS in the obese model (BMI >30 kg/m^2) compared with that of the nonobese model [24].

Typically, the surgeon's experience influences fluoroscopic use during URS. Surgeons having extensive experience with fluoroscopic surgery have less radiation exposure than trainees due to the shorter FT during URS [25]. Weld et al. investigated whether added training in safety, minimization, and awareness during radiation training for urology residents reduced the FT during URS for urolithiasis. The authors found that the residents exposed to this dedicated training had a 56% shorter mean FT than the same residents had shown earlier during their first 6 months of training (before the dedicated training) [26]. Therefore, proper education about fluoroscopy and its protocols (e.g., tactile and visual feedback) reduces their radiation exposure [27]. Similarly, for URS, the mean FT and entrance skin dose from before the radiation safety training protocols to afterward were −0.5 min and −0.1 mGy (34%), respectively [28]. Other points of which to be aware include the fluoroscopy beam, which should be collimated with the area of interest. In addition, the image intensifier should be placed as close to the patient as possible, and a pulsed fluoroscopy mode should be used to minimize radiation exposure during PCNL and URS for nephrolithiasis [29, 30]. For URS, urologists found that pulsed fluoroscopy images were adequate and equivalent for most tasks during the surgery compared with continuous fluoroscopy images [31]. Furthermore, a drape placed over or under the patient may help reduce radiation scatter. The key point for reducing patients' radiation exposure, however, is the promotion of physician awareness of the risk of radiation exposure and the importance of radiation protection.

Radiation Protection for Surgeons and Medical Staff During Surgery

The major source of occupational radiation exposure for surgeons and the medical staff is the scattered radiation produced from interaction of the primary radiation beam with the patient's body and the operating table during procedures (Fig. 4.1). Rarely, these personnel may also be exposed to direct radiation when their hands move into the fluoroscopy field between the X-ray tube and image intensifier.

Radiation scattering is divided into two types: backward and forward scattering. The backward scattering dose is approximately 20-fold as strong as the forward scattering dose [32]. Shielding against scattered radiation is usually accomplished by wearing protective clothing. The standard lead protection protocol requires the use of 0.35-mm lead aprons, thyroid shields, and eyeglasses with lead lining for the operating surgeon and 0.25-mm lead aprons for other personnel [33]. However, protection from scattered radiation by wearing protective clothes is incomplete, especially for the arms, eyes, feet, and brain.

The radiation exposure dose to the surgeon performing PCNL with a mean ED of 12.7 mSV per procedure is higher than that with 11.6 μSV during URS because of the longer FT and less distance between the source of radiation and the surgeon [8, 34]. Some investigators reported the mean fluoroscopy screening time during PCNL was 4.5–6.04 min (range 1.0–12.16 min) [35]. Furthermore, the mean radiation exposures to the finger and eye of the surgeon were 0.28 mSv and 0.125 mSV, respectively, due to the nonuniform radiation exposure to the scattered radiation [36, 37]. Therefore, operators should also protect the hands and eyes from scattered radiation exposure using gloves and glasses with lead lining. Most endourologists perform the needle puncture under fluoroscopy for renal access. The operator who carries out the needle puncture under fluoroscopy often is exposed to direct irradiation. The operator must be aware of this behavior and that it presents a critical risk. The surgeon must take care not to come into the direct fluoroscopic radiation field. The US approach is more beneficial than the fluoroscopic approach for protecting surgeons from radiation exposure during PCNL. Yang et al. reported that using a radiation shield constructed from 0.5-mm lead sheeting effectively reduces the surgeon's radiation exposure [38].

The radiation exposure dose to the surgeon in almost cases is less during URS than during PCNL because of the shorter FT and greater distance between the radiation source and the surgeon. Pulsed fluoroscopy was introduced to reduce the radiation dose by limiting the time of exposure to X-rays and the number of exposures per second. The original application of this technology during URS was decreased from 4.7 to 0.62 min [25]. Current reports have shown that the mean fluoroscopy screening time during URS was 44.1 s (range 36.5–51.6 s) [39]. In addition, incorporating several measures—using a laser-guided C-arm, last image holding, a preoperative fluoroscopy checklist—has been shown to reduce the FT by as much as 82% (from 86.1 to 15.5 s) without altering patient outcomes [40]. Currently, the RADPAD shielding device, composed of a tungsten antimony lead-free material, has been used to protect against radiation exposure during interventional radiography. This use resulted in a 23–52% reduction of the total radiation dose exposure [41]. Additionally, Zöller et al. reported that a face-protection shield was effective in reducing eye lens radiation exposure during URS [42]. Inoue and associates also reported that using protective lead curtains on both sides and at the end of the operating table and under the image intensifier was useful for reducing radiation exposure for surgeons during URS. They studied the spatial scattered radiation dose in the operating room for management of urolithiasis using an anthropomorphic phantom and ionization chamber and measured the scattered radiation dose with and without protective lead curtains under the patient's table and image intensifier. Consequently, protective lead curtains led to a 75–80% reduction in the scattered radiation dose compared to that without the lead curtains (Fig. 4.2). Additionally, Inoue et al. found these lead curtains useful for protecting against radiation exposure to surgeons during URS in the clinical setting [43] (Fig. 4.3).

Time, distance, and shielding are generally critical factors for determining the level of radiation exposure. Shielding is usually performed with protective clothing, although its protection from scattered radiation is incomplete. Inoue et al. found that the operator during URS was exposed to radiation (0.10 ± 0.47 μSv) inside the lead apron, even when wearing protective clothes. Performing procedures wearing these clothes under fluoroscopy causes fatigue because of the heavy weight of the clothes and the difficulty of movement, resulting in uncomfortable circumstances during the URS procedure. Söylemez et al. studied urologists and found that wearing

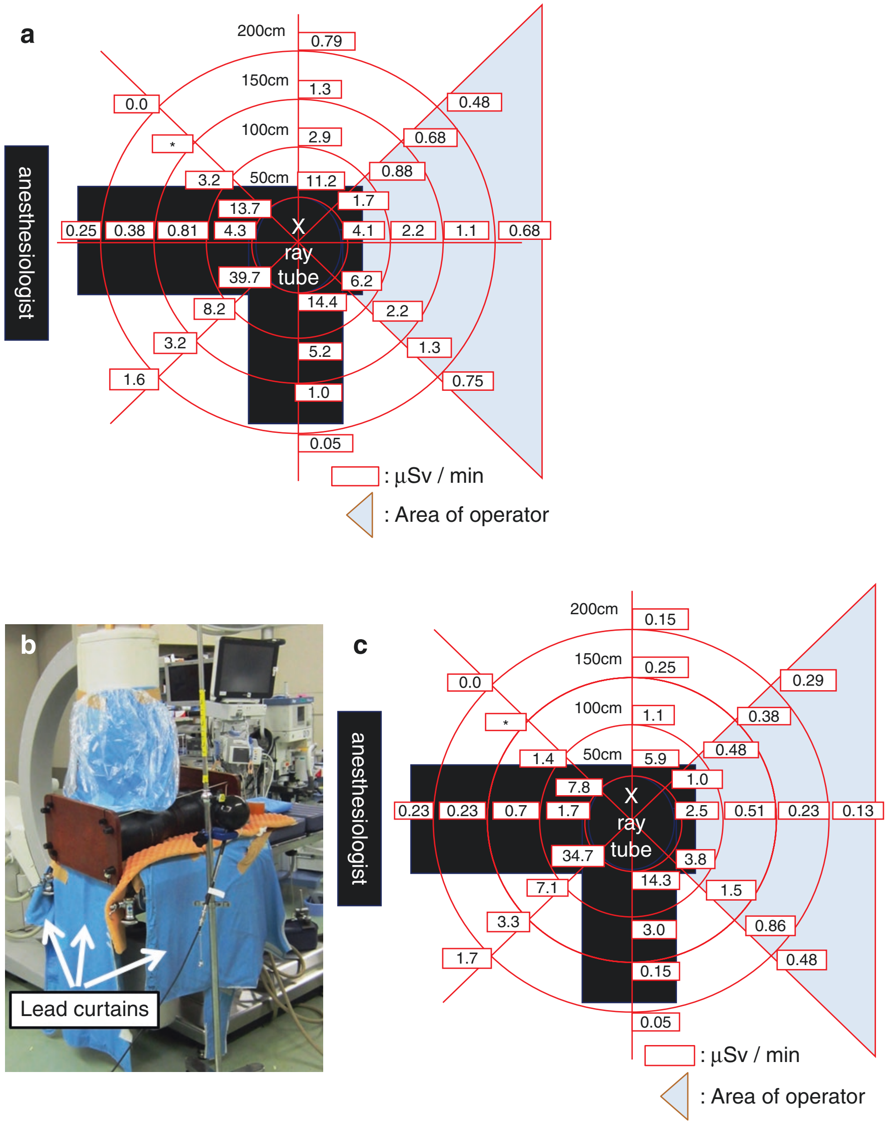

Fig. 4.2 Anthropomorphic phantom study to measure the scattered radiation dose. (**a**) Without protective lead curtains. (**b**) With lead protective curtains under the patient's table. (**c**) Image intensifier with protective lead curtains. (**b** From Inoue et al. [48], with permission of Elsevier)

protective clothing is not practical and causes deterioration of the surgeon's ergonomics [44]. Therefore, shielding from scattered radiation using protective lead devices on the operative table and circumstances may be of greater interest and potential hope.

In modern irradiation practice, active personal dosimeters are essential operational tools to satisfy the ALARA principle [45]. Most urologists have an insuffi-

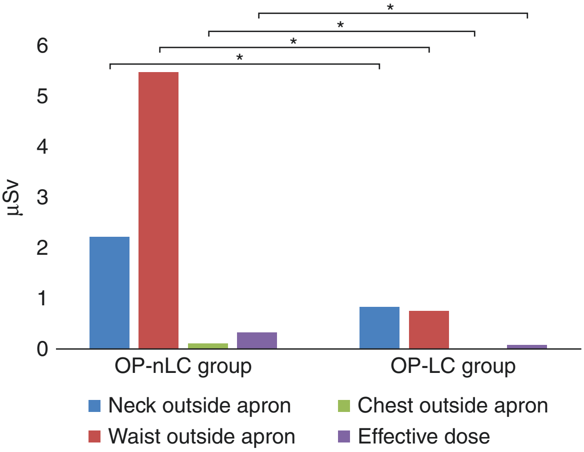

Fig. 4.3 Outcome of surgeon's radiation exposure during ureteroscopy for urolithiasis with and without lead protective curtains in a clinical study. OP-nLC group o-lead-curtain group, OP-LC group lead curtain group. $* p < 0.01$. (From Inoue et al. [48], with permission of Elsevier)

cient perception of radiation protection for themselves. A few previous studies showed that although 84.4% of urologists who were chronically exposed to ionizing radiation wore lead aprons, only 53.9% wore a thyroid shield, and 27.9% wore eye glasses with a lead lining. Moreover, only 23.6% of urologists put on a dosimeter [46]. Söylemez and colleagues found that urologists with lead aprons, a thyroid shield, eye glasses, or a dosimeter accounted for 75.2%, 46.6%, 23.1%, and 26.1%, respectively [44]. Awareness of physicians for occupational radiation exposure in the urological field remains low. Although the risks of harmful effects of occupational radiation exposure may be relatively small, they should not be ignored.

Furthermore as current technology has developed novel, robot-assisted, flexible ureteroscopes for management of urolithiasis, described by Rassweiler et al. in 2014. Although surgical outcomes—including the stone-free rate, complications, and operation time—need improvement, robotic surgery may contribute to reducing radiation exposure for surgeons and their assistants [47]. Additionally, it is potentially possible for surgeons to improve their ergonomics without wearing heavy radiation protectors.

In summary, long-term low-dose radiation exposure for patients with urolithiasis and medical professionals should not be ignored. Urologists must therefore acquire knowledge about, and the methods for, preventing radiation exposure. Other simple methods for minimizing occupational and patient radiation doses include minimizing the FT and the number of acquired images; collimating them; avoiding high-scatter areas; using the pulsed fluoroscopic mode; maximizing the distance between the X-ray tube and the patient; minimizing the distance between the patient and the image intensifier; using US instead of fluoroscopy whenever possible; using protective shielding; and wearing a personal dosimeter that provides feedback regarding the radiation dose to which one is already exposed per year (Table 4.1). Effective use of these methods requires both appropriate education and dedicated training in radiation exposure for all endourologists and their medical staff, as well as the availability of appropriate tools and equipment.

Table 4.1 Reduction technique from radiation exposure or patients and operators during surgery

Subjects	Methods ①	②	③	④
C-arm, image intensifier	Maximizing the distance between the X-ray tube and the patient	Minimizing the distance between patients and the image intensifier	Collimating	Pulsed fluoroscopic mode
Operator	Minimizing fluoroscopy time	Protective shielding for operator	Protective shielding for patient table	
Instrument	Using ultrasound instead of fluoroscopy	Laser guided C-arm	Last image hold	
Others	Dedicated educational training (including preoperative checklist)			

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