Review Article

Radiation safety and protection in urology

Jeewarit Soison, Manint Usawachintachit

Division of Urology, Department of Surgery, Faculty of Medicine, King Chulalongkorn Memorial Hospital, Chulalongkorn University, The Thai Red Cross Society, Bangkok, Thailand

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Abstract

Urologists are inevitably exposed to ionizing radiation for the length of their professional career due to medical practices in their field. However, awareness with regard to safe practices and the use of protective gear are frequently inadequate. Several studies have confirmed the potential long-term adverse effects of radiation exposure upon patients and medical personnel. All urologists, therefore, need a thorough understanding of radiation physics, and the adverse effects, safety issues, and protective measures associated with the medical practices. This understanding will serve as a foundation for the optimal utilization of radiation and the safety of patients and medical personnel.

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Introduction

The medical utilization of x-rays began in 1920 when the intensity of the radiation used was still high. Work after this point, therefore, tended to focus on minimizing the radiation dose. Over the past 30 years, there has been increasing use of imaging technology, including the emergence of different techniques, such as computerized tomography, nuclear imaging, and fluoroscopy. These practices have been widely harnessed to facilitate surgical procedures, thus leading to the rapid increase of radiology applications for medical purposes.[1] Over the last thirty years, the exposure of the U.S. population to radiation has gradually increased seven fold, with half of the exposure derived from medical radiation.[2] Urological diseases generally involve the use of radiation in various forms, from diagnosis, to surgical procedures, and follow-up. Since both urologists and patients may frequently be exposed to radiation, the urologists, as the professionals, need to be aware of its inherent hazards. This article highlights issues associated with radiation safety, potential risks, protection measurement, and the techniques which could potentially reduce such exposure.

Physics of radiation

Ionizing radiation is a type of energy emitted from atoms in electromagnetic waves or particles, which could originate from natural or artificial sources. The mechanism of image formation starts with an x-ray source that transmits photons through the atmosphere through internal organs towards an image intensifier. While traveling across the organs, the photons transfer energy to

Corresponding author: Manint Usawachintachit

Address: Division of Urology, Department of Surgery, Faculty of Medicine, King Chulalongkorn Memorial Hospital, Chulalongkorn University, The Thai Red Cross Society, Bangkok 10330, Thailand

E-mail: manint.u@chula.ac.th

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various tissues, each of which can retain a unique energy level, creating the difference in radiation intensity. When the radiation progresses to strike an image intensifier, it provides context to the image and finally produces a radiograph (Figure 1).[3]

Measurement of radiation dose

Radiation quantification usually involves the following standard units of measurement:

1. Air exposure is equivalent to the radiation amount that allows 1 kilogram of air to ionize into 1 Coulomb charge. The unit of measurement is the Coulomb (C) or Roentgen.

2. Absorbed dose is the amount of ionizing radiation absorbed by the body after passing through it while transferring some energy to the visceral organs. The unit of measurement is the Gray.

3. Equivalent dose is equal to the product of the absorbed dose and radiation weighting factor. The weighting factor is assigned to each type of radiation, mainly because a particular amount of radiation may affect tissues and organs differently. A higher amount is more likely to cause more harm to the tissues. The Sievert is used as the unit of measurement.

4. Effective dose is the sum of equivalent doses within individual visceral organs. This varies depending on the sensitivity of that specific organ, recognized because varying levels of damage occur in different types of tissues. For example, eyes and genital organs tend to have a higher sensitivity with regard to radiation than others. Despite the same amount of radiation being retained, the radiation weighting factor is thus required for accurate quantification. The unit of measurement unit is again the Sievert.[4,5]

The applications of x-rays in urology occur across diagnosis, surgical treatment, radiotherapy, and surveillance. Table 1 shows the effective dose applied for a particular procedure. Most patients with urolithiasis tend to experience recurrence, thereby have an increased risk of radiation exposure during diagnosis and treatment. One study demonstrated cumulative radiation doses ranging from 100 to 1,375 mSv.[6]

Dosimeters

All operators should have the occupational radiation exposure doses monitored by a personal dosimeter while working in radiation areas. This practice should accompany other protective measures to prevent the personnel from excessive radiation. The types of dosimeters are as follows:[7]

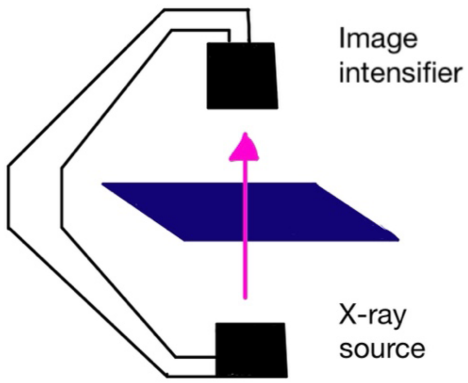

Figure 1. The x-ray image process demonstrating the x-ray source and image intensifier

Table 1. Mean effective radiation doses derived from radiographic and urological procedures (adapted from Radiation protection of patients in urology | IAEA. 2017).

Procedure	Mean effective dose (mSv)
Abdominal radiography (AP)	0.7
Intravenous pyelography (6 films)	2.5
Voiding cystourethrography	1.2
Cystography	1.8
Lithotripsy	1.3
Nephrostomy	3.4
Percutaneous nephrolithotomy	4.5
Ureteric stenting	4.7
Single-phase CT abdomen	10
Renal angiography	2 to 30

1. Film badges are composed of a layer coated with light-sensitive materials. Once radiated, the film is processed, and the intensity developed will be further compared against the standard film, ultimately providing information on the amount of radiation received. While the film badge is straightforward for daily use, it cannot detect a low level of radiation and is nor suitable for re-use.

2. Luminescence dosimeters comprise a luminescent compound that deposits a portion of incident radiation energy. The material is then stimulated before releasing energy in luminescence signals. There are two types of stimulators: thermoluminescence and optically stimulated luminescence (OSL) (Figure 2). Luminescence dosimeters are highly precise and reusable several times. Thus, they are widely utilized and are adopted at King Chulalongkorn Memorial Hospital.

Figure 2. Device demonstrating the use of optically stimulated luminescence (OSL)

3. Electronic dosimeters can quantify the radiation dose and report the results simultaneously using an electronic system coupled with a semiconductor detector. They can also give instant notification whenever the radiation dose exceeds a prescribed limit.

Those who work with radiation should at least wear two dosimeters: one beneath the lead apron to measure the radiation in contact with visceral organs, the other outside the apron, at either the collar or eye level, to detect radiation towards the skin and eye lens (Figure 3). The surgeon can use the data from both dosimeters to calculate the effective dose derived from the operation.

The International Commission on Radiological Protection (ICRP) has determined the maximum acceptable level of radiation dose for practitioners to be no more than 20 mSv each year. It may exceed the allowance up to 50 mSv per year, but the cumulative figures over five years must not be more than 100 mSv.[8] In addition, the level of safe radiation doses have been designated for different parts of the body; for example, the radiation exposure for the eye lens should not be over 20 mSv per year,[9,10] whereas the skin, arms, and legs can tolerate radiation up to 500 mSv yearly (Table 2).[11]

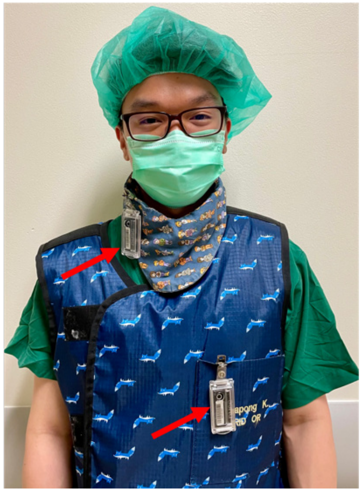

Figure 3. Position for dosimeter placement

Effects of radiation

The impact of ionizing radiation upon humans is categorized follows:

1. Deterministic effects which occur from radiation exposure above the threshold level. The severity of the damage is in proportion to the radiation dose. For example, eye injury, skin burn, and hair loss,[12] occur at exposure to 0.5, 2, and 3 Gy of radiation, respectively. These effects rarely arise from urological procedures due to the small dose of radiation applied.[13]

2. Stochastic effects occur even from exposure to a small amount of radiation. Given that there is no safety threshold limit for stochastic effects, it is essential for practitioners to be aware of the long-term consequences, mainly because exposure to low-dose radiation over time may increase cancer risk. The disease probability depends on the amount of radiation, while the severity of the disease is not dose-dependent.[14]

Three landmark studies have verified the relationship between radiation exposure and carcinogenesis:

Table 2. Occupational dose limit for each organ (adapted from 2013 Recommendations of the International Commission on Radiological Protection).

Type of limit	Occupational dose limit
Effective dose	20 mSv per year exception: 50 mSv per year (in 5 successive years <100 mSv)
Equivalent dose	
Eye lens	20 mSv per year
Local skin dose	500 mSv per year (averaged over any skin surface of one square centimeter)
Hands, lower arms, feet, ankles	500 mSv per year

- Pierce et al. conducted a study on survivors of atomic bombings at Hiroshima and Nagasaki during World War II. The authors estimated the radiation doses received at a certain distance from the bomb and compared the incidence of malignancy to an average population. They found a significantly higher incidence of solid malignancy, which was directly proportional to the radiation dose and duration since the exposure was without an apparent threshold.[15]

- Cardis et al. conducted a study on over 400,000 workers at nuclear power plants in 15 collaborating countries by measuring the radiation dose with personal dosimeters. The authors demonstrated that the incidence of leukemia and non-leukemia malignancies was directly proportional to the amount of radiation exposure. In addition, the authors speculated that 1-2% of the cancer deaths were caused by radiation.[16]

- According to a retrospective study by Pearce et al., children who acquired cumulative radiation doses of 50 and 60 mGy from diagnostic imaging experienced a 3-times higher incidence of leukemia and brain cancer, respectively, in their adulthood compared to those who never underwent such imaging. However, there remains the controversy that the patients subjected to diagnostic imaging at a younger age might already have certain abnormalities contributing to subsequent cancer risks.[17]

Even though level 1 evidence to prove the relationship between medical radiation exposure and malignancy has yet to be established, these studies, as mentioned earlier, suggest that clinicians should be aware of the potential harm inflicted by radiation.

Radiation risks to patients and medical personnel

1. Radiation risks to patients: Medical providers with protective gear receive only 1% of the radiation emitted, whereas the patients without protective equipment are directly exposed to radiation. Ferrandino et al. conducted a retrospective study on 108 patients who suffered from acute renal colic from 2000 to 2006. At the one-year follow-up, the patients received an average radiation dose of 26.7 mSv from diagnostic imaging, and more than 20% of them received radiation above 50 mSv.[18] Subsequently, Fahmy et al. conducted a similar study and demonstrated mean radiation doses given to those with urolithiasis within one and two consecutive years of 29.3 and 37.3 mSv, respectively.[19]

The recurrence rate of urolithiasis is 50% within five years; therefore, the patients are at risk of repeatedly receiving a large amount of radiation. In addition to this, fluoroscopy is commonly employed in endourology. For obese patients and those with complex cases, urologists must apply higher levels of radiation. Thus, there must be careful attention paid to radiation safety and protection.[20]

2. Radiation risks to medical personnel: Urologists, along with the other subspecialists such as radiologists, cardiologists, and vascular surgeons, have a high likelihood of being exposed to the highest radiation doses.[1]

Rajaraman et al. performed a prospective study on 90,000 radiologic technologists between 1994 and 2008. The authors found that those who work with fluoroscopy have an incidence of melanoma and breast cancer of 1.3 and 1.18 times, respectively, higher than those who did not. There was also a 2.5 times increased likelihood of mortality from brain cancer.[22] Another study determined the incidence of brain cancer among radiologists and cardiologists performing interventional procedures. More than 85% of brain cancer originated on the left side, where fluoroscopy is usually applied during the procedures. However, these results were not widely accepted as there may have been a selection bias in the study.[23]

Most studies indicated that the annual amounts of radiation received by urologists were within the limits recommended by ICRP.[24,25] In one study the average doses acquired from ureteroscopy and percutaneous nephrolithotomy were 0.03 and 0.1 mSv, respectively.[24] In this study Sparenborg et al. collected data on radiation doses the urology residents had actually received. The authors reported that the residents received an average radiation exposure of 32 mSv per year, while the attending urologists received only 8 mSv per year.[26] Although the acquired dose of urology residents was substantially lower than that determined by ICRP (i.e., 50 mSv per year), the cumulative dose over five years was still a risk.[27]

Formerly, radiation-induced cataracts were believed to be a deterministic effect with a threshold dose of 2 Sv. Still, more recent data concluded that they could be a stochastic effect without an apparent dose threshold.[28] Vano et al. performed a slit lamp examination on interventional cardiologists, nurses, and technicians. The authors found significant changes in the posterior subcapsular capsule, while the more common age-related cataract was mainly within the nucleus. Assumably, prolonged exposure to a small dose of radiation has the potential to cause cataracts through such a mechanism.[29]

Radiation protection

During the dispensing of radiological practices, urologists receive a portion of radiation dispersed from the patients.[30] As a result, medical personnel should minimize the radiation dose as much as possible based on the concept of as low as reasonably achievable (ALARA), which consists of the three safety principles: reducing time, increasing distance from the source, and using protective shielding.

1. Time. A general recommendation is to minimize the fluoroscopic time as much as possible. Lowering the frame rate by using pulsed fluoroscopy can reduce radiation exposure while still producing images with comparable quality. Canales et al. revealed that decreasing the frequency from 30 to 12.5 frames per second could decrease the radiation dose used in percutaneous nephrolithotomy by more than 30%.[31] Similarly, Smith et al. found that reducing the pulse rate helped shorten fluoroscopy time by up to 76%, minimizing the exposure by up to 64%, still giving adequate image quality to inform further procedures.[32] Other modifications may include last-hold image and collimation to optimize contrast only in the region of interest.[33] In addition, the use of a low-dose setting could reduce the radiation dosage by up to 57%.[34]

2. Distance. Increasing the distance between the radiation source and patients as far as possible is helpful because the radiation intensity declines in direct proportion to a squared distance (i.e., inverse square law). When doubling the distance from the source, the radiation emission will decrease four times (Figure 4). For this reason portable C-arm fluoroscopy is superior to a fixed table one, providing a 10-times higher radiation dose.[35] Furthermore, patients should be at the farthest position away from the radiation source where a clear vision is still attainable, yet closest to an image capturing device to lessen the chance of radiation scattering. In addition, the radiation source should be under the table to reduce exposure to important organs such as the eyes (Figure 5).[36]

3. Shielding. According to the "X-Ray MOPH Standard" by Thailand's Ministry of Public Health, radiation operators must wear personal protective equipment, including a lead apron with 0.25-mm thickness equivalence that gives 0.5 and 0.25 mm thick at the front (when folded) and back, respectively. Leaded glasses can prevent radiation from the front and side, and a thyroid shield might provide another safeguard. Hein et al. suggested that wearing protective gear can reduce the radiation exposure during ureteroscopy by up to 98%, allowing the surgeons to carry out up to 500 procedures in a year without taking up an excessive amount of radiation.[37]

A ceiling mounted screen, lateral shield, and under table curtain can further reduce the radiation dose by more than 90%. Mobile floor shields are preferable in protecting medical personnel in the circulating area. Urologists should place their hands away from an x-ray beam during the procedures unless unavoidable.[38]

A survey on the regular use of protective equipment among urologists showed that 97% of them always wear a lead apron, 67% put on a thyroid shield, and 17% use lead glasses.[39] However,

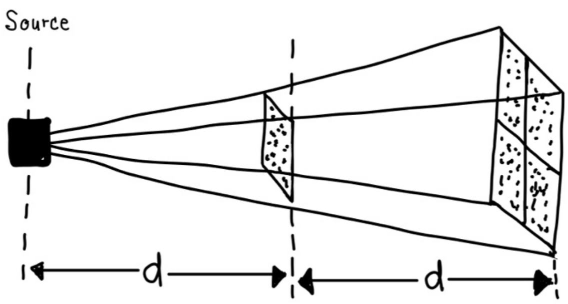

Figure 4. Intensity reduction of X-rays corresponding to the inverse square law

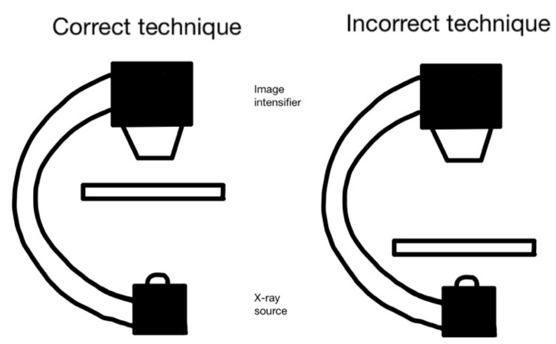

Figure 5. Appropriate positioning of C-arm to reduce radiation dosage

60% of them suffer from lower back pain and neck pain due to the lead apron, a statistic correlating with the number of procedures. Wearing a skirt-type lead apron helps alleviate lower back pain due to a better weight distribution during prolonged usage. Other anti-radiation alternatives, such as bismuth oxide and barium sulfate, are sometimes incorporated in the fabrication of lighter protective equipment.[30]

Techniques to reduce the radiation exposure

1. Techniques to reduce the exposure to radiation during stone diagnosis

Urologists should employ x-ray images only when clinically indicated. Lehnert et al. found that more than 26% of patients were unnecessarily subjected to CT scans.40 Currently, electronic medical records of x-ray images are readily available for instant access, thereby decreasing the redundancy of X-ray imaging.[41,42]

To date, a non-contrast CT scan is the gold standard for diagnosing urolithiasis due to its high sensitivity and specificity and the ability to identify renal abnormalities, stone position, and other essential characteristics. However, this imaging modality emits a high effective radiation dose.[43] A low-dose CT scan (LDCT) has been developed to reduce the radiation dosage. The low dose does lower the image sharpness and resolution, but it is still adequate for diagnosis. A meta-analysis of LDCT showed a sensitivity of 96%, a specificity of 95%,[44] and an average radiation dosage of 1.4-2.0 mSv, compared to a mean dose of 11.2 mSv from a standard dose CT scan.[45] Moreover, an ultra-low-dose CT scan (ULDCT) delivered a dosage range of 0.5-1.9 mSv, which was even lower than a plain KUB. Pooler et al. compared the diagnostic accuracy of ULDCT to LDCT for a diagnosis of stones larger than 4 mm. The authors found a sensitivity and specificity from ULDCT of 90-100% and 86-100%, respectively.[46] However, the diagnostic power of ULDCT is still limited in urinary stones smaller than 3 mm or individuals having BMI greater than 30.[47]

Using diagnostic ultrasound for urolithiasis can help reduce radiation exposure. Smith et al. randomized 2,759 individuals who visited an emergency department with suspected renal colic into three groups. The first group underwent diagnostic ultrasound by emergency physicians, the second group underwent ultrasound by radiologists, and the third group underwent an immediate non-contrast CT scan. The authors found no difference in the revisit rates due to missed or delayed diagnosis. However, the first two groups received a radiation dose of 10 mSv, while the last group diagnosed with a non-contrast CT scan received 17 mSv. Although some patients in the ultrasound groups could not obtain a diagnosis of urolithiasis and thus required a subsequent non-contrast CT scan, there was no difference in the rates of return to the emergency department, serious adverse events, and length of stay.[48]

The American Urological Association (AUA) encourages implementing ultrasound or low-dose CT scan as a follow-up imaging in assessing stone growth or new stone formation to restrict excessive radiation exposure and limit its long-term effects. Additionally, the AUA also recommends non-contrast, low dose CT scan for pediatric patients before performing PCNL.[49]

2. Techniques to reduce the radiation exposure during stone treatment

2.1 Percutaneous nephrolithotomy (PCNL) is the gold standard treatment for kidney stones larger than 20 mm or complex ones. An average radiation dose from fluoroscopy was 4.5 mSv per procedure. Obese patients with BMI > 30 may require a higher dosage. During an initial percutaneous puncture, the utilization of retrograde air pyelography rather than contrast media injection may reduce the radiation dose from 7.67 to 4.45 mSv.[50]

Other emerging techniques to reduce or eliminate radiation dose are as follows:

- Ureteroscopy-guided PCNL: By applying a flexible ureteroscope to the kidney, urologists can directly observe the needle traversing the skin into the collecting system (Figure 6). Petros et al. demonstrated that this technique could limit radiation exposure and reduce intraoperative bleeding while offering comparable stone-free rates and complications.[51] Similarly, Isaac et al. reported that ureteroscopy-guided PCNL was safe and effective, minimized the fluoroscopic time and the number of renal accesses, and yielded a higher success rate.[52,53]

- Ultrasound-guided PCNL: Ultrasound facilitates the clear distinction between anterior and posterior calyces and identifies organs surrounding the kidney, including the

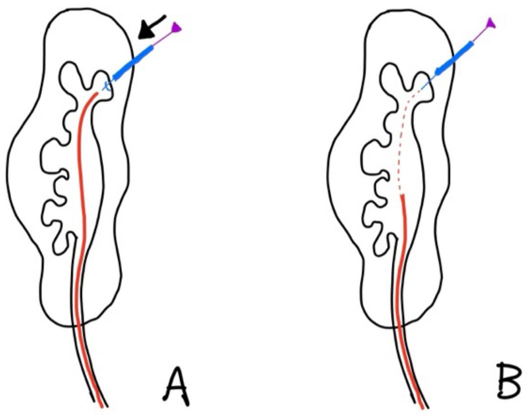

Figure 6. Ureteroscopy-guided PCNL includes: (A) puncturing the kidney via percutaneous access under ureteroscopic vision and (B) manipulating a guidewire down the ureter

diaphragm, bowel, liver, and spleen, thereby decreasing the possibility of injuring these organs. Although highly beneficial, the current evidence suggests that only 10% of urologists perform PCNL with solely ultrasound guidance, and 15% use a combination of ultrasound and fluoroscopy.[54] To safely adopt this technique, Usawachintachit el al. demonstrated that a learning curve of at least 20 procedures was essential, and indicated that the success rate might be lower in obese patients.[55] Since the utilization of fluoroscopy for obese individuals involves high exposure to radiation, incorporating ultrasound may reduce radiation usage.[56] Ultrasound guidance resulted in comparable stone-free rates, complications, and hospital stay.[57] Moreover, when integrated with the supine technique, ultrasound might also reduce costs by 30%.[58,59]

2.2. Ureteroscopy (URS) is the endoscopic treatment of urolithiasis. Although in most cases fluoroscopy is used, some urologists advocate a "fluoroscopy-free technique" with an available portable C-arm as a backup. This technique involves tactile sensation and length measurement to identify the position of each instrument, whereby some procedural steps employ ultrasound to confirm the position.[60] This approach is safely achievable by experienced urologists while operating on not too complex cases.[61] Ahmed et al. randomized 154 patients with distal ureteral stones smaller than 1 cm into two groups. The first group underwent ureteroscopy without fluoroscopy and the other group with fluoroscopy. The operative time, stone-free rate, and complications were no different.[62] Fluoroscopy-free ureteroscopy is useful for specific groups of patients at risk of radiation exposure, such as those which are pregnancy, pediatric patients, and those with multiple stone recurrence.

2.3 Extracorporeal shock wave lithotripsy (ESWL) traditionally employed fluoroscopic guidance to localize the stone. An efficacy comparison between ultrasound-assisted ESWL and pure fluoroscopic-guided ESWL showed a stone-free rate of 85.6% and 64.3%, respectively. The complication rates of these two methods were comparable. Importantly, ultrasound-assisted ESWL considerably minimized radiation exposure in pediatric patients who are more sensitive to radiation than adults.[63] In children with cystine stones, Garen et al. demonstrated a superior stone-free rate of 93.5% with ultrasound-guided ESWL, compared to 60% with pure fluoroscopy-guided ESWL. The authors concluded that the ultrasound approach is preferable in pediatric patients to prevent excessive radiation exposure.[64]

The Visio-Track (VT) locking system harnesses ultrasound for 3-dimensional localization of stones to increase precision and reduce the fluoroscopic time. Abid et al. suggested that the VT locking system yielded higher rates of efficacy than the ultrasound guidance, providing a better stone-free rate of 80% and 55%, respectively.[65]

Educating urologists about radiation safety helps minimize the overall radiation exposure.66 For urologists utilizing techniques which involve long fluoroscopic time, it is sensible to report their fluoroscopic time in comparison to the average, increasing their level of caution and highlighting the need to take appropriate action by minimizing radiation usage.[67]

Conclusion

The use of radiation is highly beneficial in endourology, especially for diagnosis and treatment. Therefore, urologists should have knowledge and be aware of issues surrounding radiation safety. They should also use the lowest possible dosage in accordance with the ALARA (as low as reasonably achievable) principle. Recently there has been the emergence of several surgical techniques to eliminate or minimize radiation exposure, which will help in this matter. Hence, urologists should study and practice those techniques to consciously restrict the use of radiation and ensure the long-term safety of both urologists and patients.

Conflict of Interest

The authors declare no conflict of interest.

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