Radiation Safety

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Patrick D. Sutphin, Steven L. Hsu, and Sanjeeva Kalva

Introduction

At the end of 2013, 421,000 persons with end stage renal disease (ESRD) were treated with hemodialysis, and the number of ESRD individuals requiring hemodialysis will continue to increase in the foreseeable future [1]. The mortality rate for ESRD patients receiving dialysis has been declining since 2002 [1]. The combination of increasing prevalence of ESRD patients requiring hemodialysis and their improved survival will continue to fuel the growth in the number of fluoroscopically-guided hemodialysis access interventions [2].

Recognizing the serious injuries arising from prolonged radiation exposure during fluoroscopically-guided procedures, the United States Food and Drug Administration issued a Public Health Advisory in 1994, which not only raised the level of awareness and concern of physicians utilizing fluoroscopy, but also prompted investigations for improvements in reduction and documentation of radiation exposure.

In addition to acute radiation exposure injuries, hemodialysis patients are at a greater risk of all-cause mortality as well as an increased risk for cancer and cardiovascular disease. These patients tend to have multiple comorbidities and risk factors that contribute to the risk of cancer and cardiovascular disease, but the traditional risk factors may not account for all of the increased risk [3, 4]. A recently proposed risk factor in hemodialysis patients for both cancer and cardiovascular disease is the cumulative exposure to ionizing radiation. Kinsella et al. performed a retrospective

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P. D. Sutphin · S. Kalva (✉)
Division of Interventional Radiology, Department of Radiology, Massachusetts General Hospital, Boston, MA, USA
e-mail: psutphin@partners.org

S. L. Hsu
Nobility Healthcare, Fortworth, TX, USA

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study of 100 maintenance hemodialysis patients with a median follow up of 3.4 years. Review of patient records found a median annual dose of 6.9 mSv per patient year and a median cumulative effective dose (CED) of 21.7 mSv over the study period. Thirteen of the 100 patients studied had a CED greater than 75 mSv. Approximately14% of the CED was related to dialysis access procedures [5]. Additional studies confirmed the elevated CED in dialysis patients [6, 7]. As survival of patients on hemodialysis improves, the elevated CED for some patients may have significant clinical impact. This chapter will focus on methods to minimize radiation exposure during fluoroscopy guided dialysis access interventions.

Definitions and Units

Radiation Exposure

Radiation exposure is the amount of electrical charge produced by ionizing electromagnetic radiation in a unit mass of air. Exposure is expressed in coulombs per kilogram or roentgens [8, 9]. The quantity of ionization of air can be correlated to absorbed dose.

Air Kerma

Kerma is an acronym for **k**inetic **e**nergy **r**eleased in matter. Kerma is measured in the clinical setting as air kerma, which is the kinetic energy released into air and expressed in units of gray (Gy) [8, 9].

Absorbed Dose

Absorbed dose (D) is amount of radiation energy absorbed per unit mass of matter. The absorbed dose can also be expressed in units of Gray, which facilitates comparison of air kerma and absorbed dose. An air kerma of 1 mGy is deemed to be approximately equivalent to an absorbed dose of 1 mGy [8, 9].

Peak Skin Dose

The peak skin dose is the highest radiation dose at a point on the patient's skin and expressed in units of Gray [10, 11].

Kerma-Area Product (KAP)

Kerma-area product is also known as roentgen-area product or dose-area product. KAP is computed by multiplying the entrance skin dose to the area of the radiation beam. KAP is expressed in Gy·cm^2. Temporal summation of KAP provides an estimate of the skin dose [8, 9, 11, 12].

Effective Dose

Performance of a radiologic examination emphasizes targeted radiation exposure for the patient. For example, when a patient with an upper extremity arteriovenous (AV) fistula presents with elevated venous pressures and prolonged bleeding at the cannulation sites following hemodialysis, fluoroscopic images should be limited to the patient's upper extremity and chest. Not all of the tissues in the upper extremity and chest have the same sensitivity to the stochastic effects of radiation. Therefore a radiation-weighting factor for each organ has been computed to take into account the risk to each exposed organ. The effective dose is the weighted sum of the doses to all exposed organs. The effective dose provides a total estimated risk to the patient from radiation exposure [8, 11, 12].

Effects of Radiation

Deterministic Effects

The deterministic effects of radiation exposure occur when a threshold radiation dose is exceeded. The severity of deterministic effects increases with the dose. An example of a deterministic effect is radiation-induced skin erythema, which occurs when a skin dose of 2 Gy has been surpassed [8, 11–13]. When the skin dose exceeds 5 Gy, then permanent partial epilation can occur, and when the skin dose exceeds 10 Gy, then permanent epilation occurs along with dermal atrophy or induration [13].

Stochastic Effects

Stochastic effects are not related to a threshold dose. The probability of occurrence of a stochastic effect increases with increasing radiation dose. Radiation-induced cancer is the most concerning stochastic effect. Although radiation exposure may not engender cancer for all individuals, increasing the radiation exposure will increase the probability of inducing cancer.

Dose Limits

The International Commission on Radiological Protection (ICRP) was founded in 1928 and has published recommendations to limit the detrimental effects of radiation for all individuals [14]. ICRP has published the recommended dose limits for radiation workers and members of the public. The following are occupational dose limits and do not pertain to planned exposure of patients.

Whole Body Dose

The ICRP recommends a whole body dose limit equal to an effective dose of 20 mSv per year averaged over a 5-year period. Thus, the total effective dose should not exceed 100 mSv during the 5-year time interval. Furthermore, within any single year, the effective dose should not exceed 50 mSv [14].

Extremity Dose

The majority of radiation exposure in hemodialysis interventions is directed at the extremity. Skin and bone are relatively insensitive to the stochastic effects of radiation, thus the ICRP dose limit for extremities is correspondingly higher compared to the average whole body effective dose. Although hemodialysis fistulas and grafts are more durable than tunneled hemodialysis catheters, fistulas and grafts typically require repeat interventions to optimize their function and prevent access loss, thus the interventional radiologist should be mindful of one's occupational exposure and also the patient radiation exposure and deterministic effects which can occur. The recommended dose limit for extremities is 500 mSv per year [14].

Methods to Reduce Radiation Exposure During Dialysis Access Interventions

Pre-procedure Planning

Reduction of patient radiation exposure begins during the pre-procedure planning phase. The details of a patient's prior interventions and associated images should be reviewed to familiarize the interventional radiologist with the patient's vascular anatomy, identify appropriate sites of vascular access, and anticipate problematic locations. Meticulous review can reduce the procedure time, utilization of the angiography suite, and dramatically lower radiation exposure.

Prior to performance of a procedure, the cumulative radiation dose should be aggregated and the dates of prior procedures should be noted. The effects of radiation exposure as it relates to skin injury are considered additive when acquired within a 60-day period [11, 15]. Any poorly functioning or completely nonfunctional hemodialysis access should be managed expeditiously. Although the cumulative radiation dose acquired within the 60-day timeframe is taken into consideration, this should not thwart prompt performance of hemodialysis access interventions. Prior recent radiation exposure should guide interventional radiologists to inform patients of the potential for skin injury.

Once the patient arrives to the angiography suite, a confirmatory ultrasound of the arteriovenous graft or fistula should be performed to verify the planned sites of access and to further elucidate the locations of the graft or fistula that may require intervention.

Procedural Techniques for Patient Radiation Dose Reduction

The principle of ALARA (as low as reasonably achievable) must be a priority when imaging patients for diagnostic or therapeutic purposes. The following are techniques which minimize patient radiation exposure and permit adherence to the ALARA principle.

Collimation

Collimation involves defining the boundaries of radiation exposure. Only the immediate location where clinical information is required should be imaged. Not only does collimation reduce radiation dose to the patient, collimation also improves image contrast and quality by reducing the scatter radiation incident on the detector (Figs. 5.1 and 5.2).

Exposure Time

Being cognizant of the radiation exposure time and making active attempts to reduce the exposure times help adhere to the ALARA principle. For a given pulse dose, reducing the exposure time, will reduce the overall patient radiation exposure. At our institution, interventional radiologists are routinely notified when the exposure time exceeds 60 min. Following 60 min of exposure time, our technologists have been instructed to communicate when an additional 5 min of exposure time has transpired. Our institutional policies adhere to the guidelines for patient radiation

Fig. 5.1 Lack of collimation: Angioplasty performed within the cephalic vein at the site of outflow vein stenosis without consideration of collimation

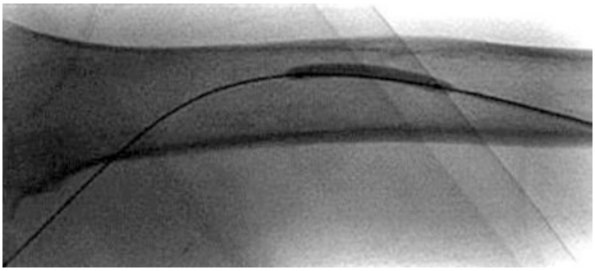

Fig. 5.2 Collimated image: Angioplasty performed within the cephalic vein at a second site of stenosis with collimation demonstrates a corresponding improvement in image contrast and quality while reducing radiation dose

dose management jointly established by the Society of Interventional Radiology (SIR) and the Cardiovascular and Interventional Radiological Society of Europe (CIRSE) [11]. The guidelines recommend informing the operator when any one of several conditions occur. These conditions include exceeding a fluoroscopy time of 60 min, surpassing an air kerma of 5000 mGy, exceeding a final peak skin dose of 3000 mGy, and accumulating a kerma-area product of greater than 500 Gy·cm^2 [11]. Knowledge of the exposure time should not prompt an interventional radiologist to cancel or inadequately complete a procedure, however, knowledge of increasing exposure times should guide the physician toward alternative procedural approaches or seek consultation from more experienced colleagues.

Object-Detector and Source-Detector Distances

The distance from the patient to the image detector should be minimized. Minimizing the distance of the patient to the detector reduces scatter and beam intensity. Conversely, the source-detector distance should be maximized. The inverse-square law states that the radiation dose to an object is inversely proportional to the square of the distance from the radiation source to the object. Thus, the procedural table on which the patient is positioned should be elevated as much as possible from the radiation source, however, patient positioning should not limit the ability of the interventional radiologist access to the patient [16] (Figs. 5.3 and 5.4).

Last Image Hold

The last image hold option should be utilized routinely to document and assist with procedural planning rather than acquisition of additional spot fluoroscopic images or performance of digital subtraction angiograms [17]. As an example, prior to stent deployment, a hand contrast injection through the access sheath can be performed to confirm appropriate positioning of the stent. The last image hold option permits the operator the ability to select the appropriate fluoroscopic image, transfer this image to a second monitor, and utilize the image to assist with accurate stent deployment.

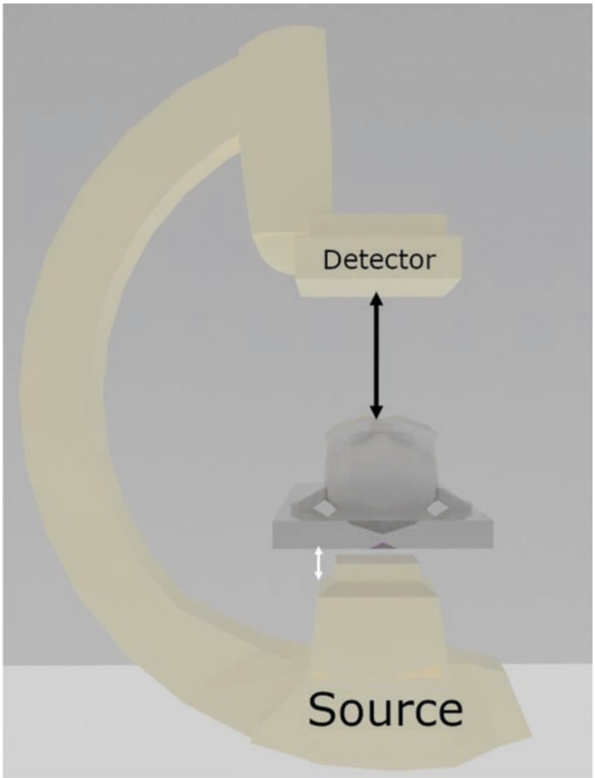

Fig. 5.3 Flat panel fluoroscopic unit. Image detector, radiation source, distance of the radiation source to the patient (*white arrow*), and distance of the patient to the image detector (*black arrow*) are identified

Reduction of Pulse Rate

The number of pulses of radiation delivered per second should be reduced to the lowest rate possible and balanced with acquisition of images of adequate quality. The default pulse rate on fluoroscopy units had been 30 pulses per second for many years [15]. At our institution, the default pulse rate has been established at 4 pulses per second, which has been deemed adequate for acquisition of quality images. However, procedures such as catheter placements and tube exchanges, which do not require complex catheter and wire manipulations can be performed with pulse rates of 2 per second. Reduction of the fluoroscopic pulse rate has been shown to reduce radiation dose [18].

Digitally Subtracted Angiography

Digitally subtracted angiography (DSA) is an image processing technique in which a radiographic digital image of the area of interest is acquired prior to the delivery of contrast material. This image serves as the mask image. The mask image is

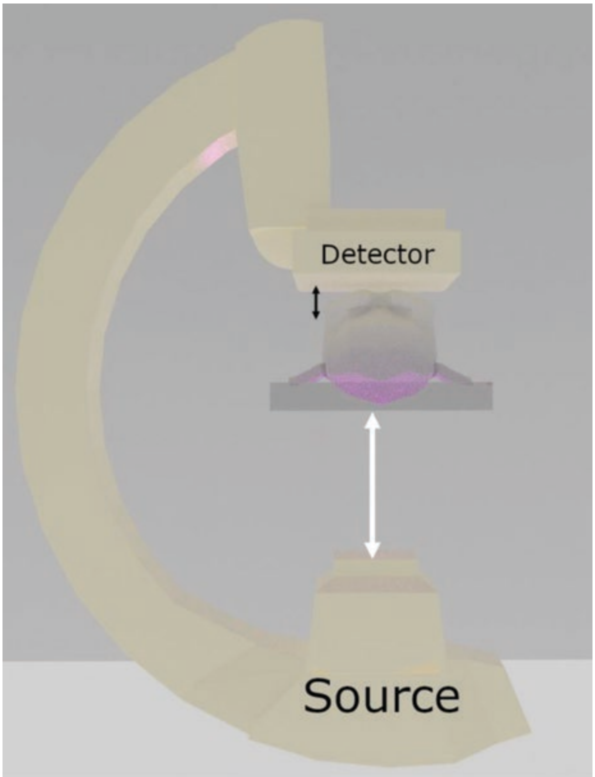

Fig. 5.4 Flat panel fluoroscopic unit illustrating minimization of distance from the image detector to position of the patient on the procedural table (*black arrow*) and maximizing the distance from the radiation source to the patient on the procedural table (*white arrow*)

subsequently subtracted from subsequent digital radiographic images obtained following the arrival of contrast material. The resulting subtracted image is then enhanced through the expansion of the dynamic range [19]. DSA provides high quality images with the trade-off of higher radiation exposure [20]. A review of 764 vascular procedures over a one year period, revealed that 70% of the DAP was secondary to the acquisition of radiographic images. The authors concluded that the DAP could be significantly reduced through the use of fluoroscopic scenes to document findings, when feasible, compared to DSA images [20].

Road Mapping

A road map can be created through contrast material injection into the hemodialysis graft or fistula or through performance of a digital subtraction angiogram. The image following contrast material injection that delineates the outflow vessels can be displayed overlying real-time fluoroscopy images. This permits the interventional radiologist with a vascular map—“road map”, to navigate through vessels without additional contrast enhanced images or digital subtraction angiograms, thus minimizing the patient’s radiation dose [8].

Documentation of Radiation Exposure

An essential component of an effective radiation safety program within healthcare facilities where fluoroscopy-guided procedures are performed is documentation of patient radiation exposure. Designing an appropriate workflow for the documentation to ensure the uniform and accurate documentation of radiation exposure either through automated or manual means. As stated before, the radiation dose from prior interventions will need to be rapidly retrieved, reviewed, and aggregated as part of the pre-procedural planning phase. Radiation dose monitoring software is available to facilitate the collection and storage of radiation dose information.

Ultrasound

Alternative modalities to radiographic evaluation and treatment may be employed to reduce radiation exposure. Ultrasound-guided dialysis vascular management has been described as a method to guide balloon angioplasty in the treatment of dysfunctional dialysis access [21–23]. In a study of 189 ultrasound-guided balloon angioplasties of dialysis access, 127 (67%) were performed without the use of fluoroscopy. The reason for procedural failures included difficulty in transversing aneurysmal segments and anastomotic stenoses [22]. Ultrasound-guided dialysis access management has also been performed in the office setting without immediate fluoroscopy backup [23].

Image Noise Reduction

The available equipment for procedures also plays an important role in reducing radiation exposure. The perception of image quality is inversely proportional to image noise. Noise reduction algorithms had previously been applied to photographs, particularly those obtained in low light settings. Söderman et al. adapted the concept of noise reduction to radiographic images. The noise reduction algorithm they designed reduced radiation exposure by 75% in digitally subtracted angiograms in neuroradiology without loss of image quality [24].Though this technology has not been specifically studied in the context of dialysis access interventions, this technology has the potential to reduce radiation exposure in multiple vascular beds [25, 26].

Patient Follow-Up

The SIR guidelines recommend follow-up clinic visits for patients who have received a significant radiation dose. A significant radiation dose can be implied when conditions arise whereby the operator is alerted per SIR/CIRSE guidelines. This includes attaining a peak skin dose of greater than 3000 mGy, a reference point air kerma of greater than 5000 mGy, a kerma-area-product greater than 500 Gy·cm^2 or when the exposure time has exceeded 60 min [11, 15]. A follow-up visit can be set approximately 2 weeks from the date of the procedure to correspond to the time when transient erythema and epilation will manifest [15].

Radiation Exposure to the Interventionist

Interventionists are also at risk from the cumulative effects of ionizing radiation over a career of performing fluoroscopy-guided interventions (Fig. 5.5). The standard radiation shielding apparel should apply in dialysis interventions including lead apron, thyroid shield, leaded glasses with lateral protection, as well as radiation shields which may be floor, table, or ceiling mounted. Strategies to minimize the use of radiation may also be employed, such as the use of ultrasound described above to both evaluate dialysis access and guide balloon angioplasty.

Manual-injection DSA is often performed in dialysis access management. In a review of procedures performed with manual-injection DSA, Hayashi et al. found that greater than 90% of operator exposure was related to manual injection. Based on these findings it was recommended to either use a power injector to avoid radiation exposure or maintain a position as far away from the patient as possible while performing manual injection DSA [27].

The anatomic nature of dialysis access procedures predisposes hands to higher levels of radiation. A retrospective study by Stavas et al. found that radiation exposure to the hands was relatively high during restoration of flow in clotted dialysis access grafts [28]. Radiation exposure to both the right and left hands was tracked through the use of thermoluminescent ring dosimeters on each hand of five interventional radiologists over a total of 62 synthetic graft declot procedures. The mean right hand exposure was found to be 0.78 mSv, and the mean left hand exposure was 0.55 mSv. No patient-related factors such as position of the graft, age, sex, previous thrombosis or number of previous interventions were found to be significant factors in hand dose. On the other hand, technical factors such as fluoroscopic time and the number of angiographic runs were significant factors in total hand dose. In comparison, a multicenter study of radiation exposure found the median exposure of one hand per procedure to be 0.075 mSv over a wide variety of procedure types [29]. Similarly, a prospective single institution study found the average hand dose to be 0.0996 mSv over a variety of endovascular procedures including coronary angiography, pelvic angiography, and lower and upper extremity angiography [30].

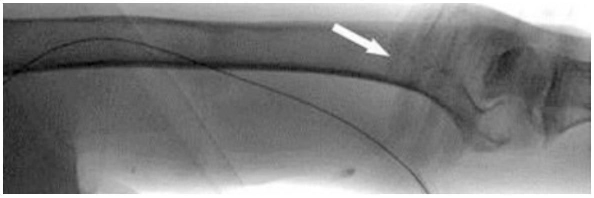

Fig. 5.5 Fluoroscopic image taken from a fistulogram with interventionist's hand (*arrow*) in the field of view

The recommended annual occupational limits to the hand are 500 mSv by both (IRCP) and the National Council on Radiation Protection and Measurements (NCRP) [30]. Although it would take greater than 600 declot procedures to exceed the recommended exposure limits of 500 mSv, it is important to recognize the increased exposure during declot procedures and develop strategies to minimize exposure. Several strategies have been explored in addition to reducing fluoroscopic time and the number of angiographic runs. These strategies include the use of leaded shields, leaded gloves, and radioprotective drapes. The use of a disposable radioprotective bismuth drape demonstrated a marked reduction of hand exposure by 29-fold [31]. A relatively new development is the introduction of an x-ray attenuating lotion which contains bismuth oxide (Bi_2O_3) ceramic powder (UltraBlox by Bloxr, Salt Lake City, UT) and can be applied to the hands [32].

Dialysis access thrombectomy tends to be the procedure associated with the greatest radiation dose both to the patient as well as the interventionist. One additional technique to reduce both the procedure time and radiation exposure in thrombectomy is the use of tissue plasminogen activator (tPA). One study compared the use of mechanical thrombectomy versus mechanical plus "no-wait lysis" on the procedure time and radiation exposure. The no tPA group had an average procedure time of 55.5 min and the "no-wait lysis" group had a procedure time of 27.2 min and fluoroscopy times were reduced to 159 seconds in the "no-wait lysis" group from 243 seconds in the no tPA group [33].

Conclusion

Given the potential for serious patient injuries and long-term ill effects resulting from cumulative radiation exposure, meticulous pre-procedural planning should be undertaken and techniques for radiation reduction must be optimized. The ALARA principle is the guiding principle for all proceduralists utilizing fluoroscopy. Although much attention was been made toward patient radiation dose reduction, it should be mentioned that optimizing patient dose management translates into optimal operator dose management and provision of high quality patient care.

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