Radiation Dose and Radiation Protection for Patients and Physicians During Interventional Procedure#

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Angioplasty/Catheterization/Radiation dose/IVR.

Although the wide acceptance of interventional radiology (IVR) procedures has led to increasing numbers of interventions being performed, the radiation doses from IVR are higher. Increasing numbers of case reports of patient radiation injury resulting from IVR are being published. Therefore, radiation protection during IVR poses a very important problem. To protect against radiation injury, the evaluation of radiation dose is essential. The radiation dose must be evaluated for each IVR x-ray machine and each laboratory, because it varies greatly. To obtain this information easily, and to ensure practical use of the radiation information, good relationships between interventionists and medical physicists are essential.

INTRODUCTION

Many patients benefit greatly from interventional radiology (IVR) procedures such as percutaneous coronary intervention (PCI) and cardiac radiofrequency catheter ablation (RFCA); however, a major disadvantage associated with these procedures is patient radiation exposure.1–7)

Currently, IVR procedures tend to be complex, which increases the fluoroscopy time and delivers high radiation doses to both physician and patient. Therefore, radiation protection for the physician and patient during IVR constitutes a very important problem.

The biological effects of radiation are of two types: stochastic (such as radiation-induced cancer) and deterministic (such as erythema). Currently, one of the most important problems in IVR is the occurrence of the deterministic effects of radiation because the number of case reports documenting patient skin injuries from IVR is increasing.8–14)

This review describes radiation dose and radiation protection for patients and physicians during IVR.

PATIENT DOSE

Patient dose quantities

Figure 1 shows the dose parameters used to describe patient radiation exposure during IVR.

Dose-area-product (DAP): The DAP can be measured using

Fig. 1. Patient dose quantities in IVR. IRP: Interventional reference point, ESD: Entrance skin dose, DAP: Dose-area-product.
specially designed ionization chambers mounted at the collimator system. The cumulative DAP is the sum of the products of the doses and the areas of the x-ray fields for all segments of an IVR procedure. DAP can be helpful in dose control with regard to the risk of a stochastic effect to patients.

**Interventional reference point (IRP):** The IRP is located 15 cm from the center of the isocenter of an IVR x-ray unit on the central beam towards the focus. The cumulative dose at the IRP is the sum of the doses at the IRP for all segments of an IVR procedure. For many cardiac IVR procedures (oblique view), this location (IRP) approximates to the location of the skin at the beam entrance point.

**Entrance skin dose (ESD):** The ESD is the dose absorbed in the skin at a given location on the patient. The total ESD (TESD) is the sum of the ESDs for all segments of an IVR procedure. If the angles and views used while performing IVR procedures are constant, the patient’s maximum skin dose (MSD) will be the same as the TESD. However, the angles and views and translation of the x-ray tube in most IVR procedures are not constant, so the portion of the patient skin exposed will vary. Therefore, the MSD will not be the same as the TESD in IVR. Typically, the TESD is greater than the MSD.

**Patient skin injury**

Although increasing numbers of case reports of patient radiation injuries resulting from IVR are being published, these reports probably represent a small fraction of actual cases of injury, as there seems to be little awareness or appreciation of radiation-induced injury in IVR (Fig. 2). In many cases, the connection to IVR is not made or the pathology is initially attributed to other factors. To protect against patient skin injury, the MSD should be monitored in real-time.

**Comparison between RFCA and PCI**

The risks of PCI and RFCA are lower than those of surgery. Consequently, their wide acceptance has resulted in an increasing number being performed. This is despite the radiation doses from cardiac IVR being the highest of any commonly performed general x-ray examination. For example, although RFCA is a very useful approach for treating cardiac arrhythmias, many radiation skin injuries have been reported with RFCA.8,9,22,23)

The radiation associated with PCI in our previous studies was often spread widely and was variable, although we did observe a tendency with regard to the MSD location and area when we analyzed the data separately for different target vessels.24) In contrast, the locations for the MSD during RFCA were more specific and within a narrow range, because the angles and views used while performing the RFCA procedures were essentially constant (30° right anterior oblique and 45° left anterior oblique views). Figure 3 shows the location (center) of the MSD in the RFCA cases (n = 40); there is no large scatter (right or left back skin). Figure 4 shows the location (center) of the MSD in the PCI cases (n = 197); there was large scatter.

For RFCA, the MSD value for atrial fibrillation (AF) patients was greater than that for other arrhythmia patients (p < 0.001), which is similar to previous reports.22,23) One of

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**Fig. 2.** Radiation injury (main erythema, right mid back) following percutaneous coronary intervention (PCI). (6 weeks after PCI. Estimated skin dose, 8 Gy). Radiation skin injury in interventional radiology (IVR) is overlooked clinically in many patients. Many patients likely suffer radiation effects, particularly after unusually difficult IVR, although they may not be aware of this or the risk it represents.

**Fig. 3.** Location of the patient’s maximum skin dose (MSD) in all of the cardiac radiofrequency catheter ablation (RFCA) procedures (n = 40). The location of the MSD was evaluated by using the center of the MSD area given by the CareGraph (Siemens). The radiation associated with RFCA was spread narrowly (right or left back). (Modified from reference 15).
the most likely reasons for the larger MSD is that RFCA is more complex in AF compared with the other arrhythmia types, necessitating a longer fluoroscopy time for the AF patients than for the other patient groups (Table 1). (In this study, RFCA was performed without using an electroanatomic mapping system).

Table 2 compares RFCA and PCI in our previous studies.15,24–26) The MSD values were significantly lower for RFCA than for PCI, although the total fluoroscopy duration was longer during RFCA than during PCI. This is because RFCA uses a lower-frame rate of pulsed fluoroscopy than PCI (7.5 vs.15 pulses/s, respectively) and a larger image intensifier (I.I.) field than PCI (23 vs. 17 cm, respectively), both of which are associated with lower radiation exposure. The MSD area was significantly larger for RFCA than for PCI owing to the large I.I. field used during RFCA.

Based on the strong correlation between the MSD and TESD or DAP in RFCA procedures, the TESD and DAP appear to be good indicators of the MSD during RFCA (Table 2). In addition, the r values for the correlations between the MSD and the indicators such as the DAP were higher for RFCA than for PCI. The lower r value for PCI is primarily due to the use of different angles and views while...
performing PCI.

The MSD constituted 44% of the TESD for RFCA, which is somewhat lower than the percentage for PCI in our previous study (Table 2). This is likely to be attributable to the use of a biplane imaging system with constant angles and views, which spreads the MSD, in RFCA.

Measurement of the radiation dose

Table 3 summarizes representative tools for determining the patient dose in IVR. The radiation exposure to the patients’ skin during IVR has been measured accurately using thermoluminescent dosimeters (TLDs). Radiophotoluminescence glass dosimeters (RGDs) can also measure patients’ skin doses accurately during IVR. Although TLD and RGD are effective tools for measuring the skin dose, real-time measurements are not feasible using these methods. The skin dose monitor (SDM) was a practical device for measuring skin radiation in real-time during IVR. However, it is no longer available because of toxicity concerns associated with its zinc–cadmium sensor.

Two-dimensional measurement methods are better tools for determining two-dimensional doses, although it only estimates doses of up to 5 Gy. This tool can evaluate the dose distribution and the MSD area, but the method does not provide real-time evaluation.

The CareGraph is a useful tool for indirectly measuring the MSD in real time. The CareGraph algorithm uses several factors to calculate the patient skin dose, including the measured DAP, x-ray parameters, and position. However, the CareGraph can only be used with Siemens machines (Bicor or Multistar angiographic units). In addition, the CareGraph is no longer available on newer Siemens equipment.

Estimation of the radiation dose

As described above, there is no ideal real-time measuring method for the MSD in IVR. As a result, the MSD is estimated using several factors, such as fluoroscopic time, i.e., without using a dosimeter.

The fluoroscopic time is the factor that the Food and Drug Administration (FDA) and International Commission on Radiological Protection (ICRP) recommend be monitored during fluoroscopically guided IVRs, although fluoroscopic time is a very rough predictor of the MSD in IVR.

The DAP is the absorbed dose to air (air kerma) multiplied by the x-ray beam cross-sectional area at the point of measurement. Miller et al. reported that the MSD and DAP were correlated in IVRs. We previously reported a strong correlation between the MSD and DAP in RFCA procedures (r = 0.94, p < 0.0001), but we did not find good correlational trends between the MSD and DAP for PCI procedures overall (r = 0.712; Table 2). However, when we analyzed the relationships for different target vessels separately, we did find good correlational trends between the MSD and DAP for PCI procedures performed in the right coronary artery (RCA, American heart association segment number (AHA#) 1–3: 0.871, AHA #4: 0.898), but not for

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<th>RGD</th>
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| TLD: thermoluminescent dosimeter. |
| RGD: fluorescent glass dosimeter. |
| SDM: skin dose monitor. |
| RSI: radiosensitive indicator. |
those in the left coronary artery (LCA, AHA #11–15: 0.628, AHA #5–10: 0.694). Therefore, the DAP may be suitable for estimating the MSD during PCI in the RCA. The dose at the IRP has been reported to be helpful for characterizing patient exposure in real-time. The cumulated IRP value (cumulative dose) for IVR can probably be a surrogate measurement for the TESD. However, only very modern x-ray machines display the dose at the IRP. Nevertheless, Miller et al. reported that the MSD and the dose at the IRP were correlated ($r = 0.862$) in IVRs. In addition, Hirshfeld et al. reported that IRP values are overestimates of the MSD and have a margin of error that may be as much as a factor of 2 or greater.

The PEMNET system calculates and displays the real-time exposure rate based on several parameters, such as kVp, mA, and the geometry of the table. Consequently, the PEMNET system can provide real-time monitoring of patient exposure, calculated from the acquisition parameters, but the value PEMNET displays is the same as the TESD, not the MSD.

Currently, angiographic x-ray units can probably display a value equivalent to the TESD in real-time and the dose at the IRP. We investigated the relationship between the MSD and TESD to determine whether the TESD can be used to estimate the MSD during PCI. Significant correlations were observed between the MSD and TESD during PCI (Table 2). Therefore, the TESD is the most effective real-time predictor of the MSD during cardiac IVR. However, the TESD does not evaluate the dose distribution or MSD area.

**Radiation reducing/optimizing methods (Table 4)**

The fluoroscopic beam should be on only when the dynamic information from the fluoroscopy image is being utilized actively. The ICRP recommends that physicians “keep beam-on time to an absolute minimum—the golden rule for control of dose to patient and staff.”

As the fluoroscopy/acquisition input dose decreases, the patient radiation dose decreases, but image noise increases. The optimal input dose mode (i.e., the best balance between image noise and radiation dose) is necessary. The goal is to produce a usable image, not a perfect one!

To reduce the radiation dose, the recording speed must also be reduced. Baim reported that some laboratories record coronary images at speeds as low as 15 frames/s during acquisition (cine). Scanavacca et al. reported that during cardiac catheter ablation, the use of pulsed fluoroscopy at 7 pulses/s decreased the radiation exposure time by 80% compared to conventional fluoroscopy, without affecting the procedure duration or success rate.

Increasing the x-ray tube potential decreases its absorption, enabling the penetration of dense body parts, and reduces patient exposure by reducing the fraction of the beam absorbed by the patient. However, as the x-ray tube potential increases, the differences in relative absorption of different tissues decrease. This decreases beam modulation and reduces image contrast. Therefore, optimal x-ray imaging requires a compromise x-ray tube potential that produces the best balance of x-ray tube potential, image contrast, and patient dose.

Additional beam filters have appreciable photoelectric absorption at low photon energies. The attenuation of patients’ superficial tissues decreases with increasing photon energy. Placing an aluminum or copper disk on the output port of the x-ray tube preferentially removes low-energy photons from the beam, thereby reducing the dose absorbed by the patient.

Collimating to the area of interest reduces exposure by reducing the volume of tissue that is irradiated. As a result, it also reduces scattered radiation within the patient. By reducing scatter, collimation also improves image quality. In addition, beam collimation does not reduce the entrance port radiation dose rate. Collimation can reduce the accumulated dose to the skin by eliminating the overlap of fields when different beam angles are used.

For conventional I.I.s, the dose generally increases substantially with increasing magnification, although the increased magnification produces better spatial resolution. This is another example of the conflict between image quality (spatial resolution) and dose reduction in I.I. Flat-panel detector (FPD) systems may have a smaller dose increment with magnification as compared with no magnification, although the increased magnification produces essentially no change in spatial resolution.

The patient dose increases with increasing image-receptor-to-patient (i.e., image-receptor-to-x-ray tube) distance because the x-ray outputs become higher. Therefore, the x-ray system should be positioned so that the distance from the patient to the image detector is minimized. Furthermore, the distance between the x-ray tube and patient should be maximized as much as possible. Placing the x-ray tube too close to the patient’s body can greatly increase the dose to the skin.

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**Table 4. Radiation reducing/optimizing methods (Main factors)**

- Minimize beam-on time, both for fluoroscopy and acquisition
- Lower dose-mode fluoroscopy/acquisition
- Lower recording speed
- Higher X-ray tube potential
- Additional beam filtration
- Proper collimation of the primary beam
- Minimize the use of image intensifier magnification
- Keep image receptor as close to patient as possible
PHYSICIAN DOSE

Importance of radiation protection

Physicians have been injured performing some IVRs. Furthermore, most physicians stand close to the patient where the dose and scattered radiation are higher; hence, physician doses are higher. Therefore, radiation protection for the physician during IVR poses a very important problem. Decreasing the dose to the patient will also decrease the dose to physician. Therefore in many cases, the methods for reducing the patient radiation dose are the same as the methods for reducing the physician dose.

Sources of physician-received scatter radiation (Fig. 5)

There are two sources of scattered radiation, the patient (including the catheter table) and the surface cover (exit port) of the x-ray beam-collimating device. The x-ray tube housing incorporates lead shielding that absorbs all x-rays except those emanating from its exit port. When an under-table x-ray tube system (and posteroanterior view) was used, the lower part of the physician’s body received high scatter radiation. Optimal collimation reduces scattered radiation within the patient and in the procedure room, reducing both patient and physician exposure.

Three-point policy of external radiation protection

The three-point policy of external radiation protection for staff is to reduce the exposure time, increase the distance from the radiation source, and use radiation shielding. Currently, IVR tends to involve long procedures (long radiation duration), and physicians are close to the source of scatter radiation. Hence, shielding is a critical means of radiation protection for IVR staff, especially physicians.

Additional lead shielding-devices

One of the most important means of protecting the physician from scattered radiation is to use additional lead shielding-devices, such as tableside lead drapes and ceiling-mounted lead acrylic protection. Although additional lead shielding-devices provided extra protection to the physician during cardiac IVRs, the reduction in the estimated physician dose with additional shielding was lower than we expected. One of the most likely reasons for this is that, at times, the additional lead shielding-devices could not be positioned appropriately between the point at which the x-ray beam enters the patient’s body and the physician during the procedure, given that additional lead shielding-devices are somewhat cumbersome in a clinical setting. Therefore, manufacturers must develop more ergonomically designed protection devices for cardiac IVR.

Usefulness of non-lead aprons

Because conventional lead protective aprons are heavy as they are made of lead, so the physician may not tolerate wearing one for long procedures. As non-lead aprons consist of composite materials, mainly W and Sn, they are approximately 20% lighter than lead aprons. And non-lead aprons are nontoxic. The protection performance of these non-lead and lead aprons was similar for scattered x-rays. Therefore, non-lead aprons are more suitable in providing radiation protection for IVR physicians.

Radiation monitoring for physicians

Electronic pocket dosimeters are used for the real-time monitoring of exposure from radiation source. To protect against radiation injury, the evaluation of radiation monitoring (effective dose: ED) for physicians is essential. The most important issue is that all IVR physicians must wear their monitoring devices consistently and that their recorded dose must be studied regularly to ensure that occupational
Table 5. Different formulas are used for estimating the effective dose (ED)

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<th>Formula</th>
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<tr>
<td>ED = 0.5Hin + 0.025Hout</td>
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<tr>
<td>ED = 0.3Hout</td>
<td>One dosimeter</td>
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<tr>
<td>ED = Hin</td>
<td>One dosimeter</td>
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Hin: the dose of the chest or waist badge under the lead shield (personal lead apron).
Hout: the dose of the neck (collar) badge outside the lead apron.

暴露 remains within the maximal allowable limits.

Generally, the radiation dose to IVR physicians is nonuniform. Therefore, single dosimeter methods during IVR procedures will be insufficient for assessing ED. Hence, the two-monitor method should be used to estimate the ED during IVR procedures. In addition, several different formulas are used to convert exposure data into ED (Table 5). As a result, the ED depends on the monitoring method (one versus two monitors) and the formula selected for calculating ED. Therefore, physicians should consider these findings, especially when comparing the ED levels among laboratories.

CONCLUSION

Although patients greatly benefit from IVR procedures, a primary disadvantage associated with IVR procedures is radiation exposure. Therefore, radiation protection during IVR poses a very important problem. To reduce the risk of radiation injury to patients, physicians should be aware of the details of the patient radiation dose of the x-ray system that they use for IVR. In addition, decreasing the dose to the patient will also decrease the dose to staff. Consequently, we must emphasize the importance of good relationships between interventionists and medical physicists, without which optimal radiation safety cannot be achieved.

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REFERENCES

15. Chida K (2008) Patient radiation dose in cardiac interven-


