The idiom “double-edged sword” describes the use of ionizing radiation in the field of medicine. Medical radiation from x-rays and nuclear medicine is the largest man-made source of radiation in Western countries and although it has benefited patients there is an associated liability or health risk that is unavoidable. A 2009 report by the National Council on Radiation Protection and Measurements found the total exposure to ionizing radiation in the United States has almost doubled during the past 2 decades. This finding is to a large part attributable to the rise in cardiovascular diagnostic and therapeutic interventions, which are responsible for ≈40% of the cumulative effective dose of radiation to the population exclusive of radiation oncology. As a field, interventional cardiology has flourished with the advent of technology to allow the treatment of more complex coronary artery disease and expansion in the arenas of endovascular and structural heart disease. With our success comes a heavy burden, that of awareness of the hazards of radiation, appropriate use and documentation of exposure, and constant effort to achieve the lowest achievable exposure necessary to care for an individual patient.

Defining Radiation Exposure

There are various measurements of radiation exposure; therefore, familiarity with the nomenclature is required to understand the risks. The effective dose, measured in millisieverts (mSv), is a whole-body dose independent of where the radiation is delivered and permits comparisons among exposed individuals. For reference, background exposure to an individual in the United States is ≈3 mSv/yr. Cardiac radionuclide studies have an exposure range of 15 to 35 mSv and invasive diagnostic cardiac procedures generally 1 to 10 mSv, whereas interventions can have substantially higher exposure. Most modern catheterization laboratory equipment measures air kerma, which is the energy delivered at a certain point in space (unit of measure is gray [Gy]) to assess hazard at a particular location, and kerma air product or dose area product, which takes into account the area of the x-ray beam (Gy/cm²). The effective dose can be roughly estimated by multiplying the dose area product by 0.26.5

Risk to Patients and Physicians

Deterministic risks of radiation are well described. There are known exposure thresholds for tissue injury that are relevant to patients, such as skin erythema (≈2 Gy) and permanent skin injury (≈5 Gy). For operators, the eye lens is susceptible and cataracts risk increases with acute exposure as low as 0.1 Gy and chronic exposure of 5 Gy. Stochastic effects, including cancer, have a long latency period and the lifetime attributable risk is difficult to quantify. Because of the radiosensitivity of tissues, children have the highest risk, followed by adult women, adult men, and then the elderly. Evidence to support the carcinogenic effect of radiation in patients is strong. The malignancy risk for physicians practicing today is less clear and controversial, but certainly the risk is not zero. Disturbingly, studies have shown significant deoxyribonucleic acid damage in physicians chronically exposed to low-level radiation, and cases of left-sided brain tumors and other cancers among interventional cardiologists are widely discussed.

What is concerning is that interventional cardiologists rank among health professionals with the highest radiation exposure; however, one positive note is that there is a evidence of lower exposure over time. In a high-volume, single-center study, occupational doses recorded were 7- to 14-fold lower in 2006 when compared with that in 1989 to 1992. The reduction was attributed to newer equipment, implementation of training in radiation protection, and systematic use of ceiling suspended protective screens. Unlike patients, who have a few concentrated exposures, physicians have a low-level continuous exposure. A particular period of vulnerability is during fellowship training and the learning curve of a new procedure (eg, transradial catheterization). In these situations, fluoroscopy time and radiation exposure are generally greater, and attention is focused on safely completing the procedure at hand rather than on occupational safety. Because formal training in radiation protection is effective in reducing radiation exposure in our field, mandatory training of fellows and periodic retraining of seasoned operators is imperative. The use of simulation for new procedures or trainees may result in lower radiation exposure, but this has not been examined.

Equipment

Most cardiac catheterization laboratories in the United States have newer equipment, including digital imaging technology and flat-bed panel detector systems. When compared with older image intensifier systems, the newer detectors have increased sensitivity to x-rays and improvement in spatial resolution, which may result in sharper images. The change
from an image intensifier to a flat panel detector, however, does not assure a reduction in radiation dose. On the contrary, an increase in patient dose can occur if attention is not given to the settings on the new systems. The newer equipment may not generate less radiation per pulsed frame (comparisons are unavailable between old and new systems) but have several features that have resulted in lower exposure, including real-time monitoring of patient exposure, alarms to mark fluoroscopy time, adjustable pulsed fluoroscopy and acquisition rates, fluoroscopy save, virtual collimation, digital magnification, automation of projections, and optimization of x-ray tube position.

In the current systems, x-ray is delivered in a pulsed mode to prevent bluriness and in the United States the standard video frame rate is 30 frames per second (FPS). Typically, the fluoroscopy acquisition (sometimes referenced to as CINE rate) for adults is set at 15 FPS. Lowering the pulsed frame rate does not cause flicker because of frame hold or image linking, but motion jerkiness increases with decreasing frame rates. The pulsed fluoroscopy and acquisition rates can both be adjusted. Acquisition requires higher energy input doses than pulsed fluoroscopy by 7- to 15-fold, but since fluoroscopy time is greater than acquisition time reducing both pulsed frame rates is advantageous. The quantitative dose per pulse is not fixed across systems but is regulated by the x-ray equipment to maintain image quality; therefore, a decrease in rate is not proportional to a decrease in radiation. How acceptable an operator finds the images using lower pulsed fluoroscopy rates depends on several factors, including visual processing ability, patient size, cardiac motion, image magnification, complexity of the procedure, and expectation of image quality. Many physicians are unaware of or do not use the radiation-reducing capabilities of current systems and many systems do not allow manipulation of the settings by the physician or catheterization laboratory staff. A reasonable expectation of manufactures is to provide a measure that can be compared across systems, such as nGy per pulse for fluoroscopy and acquisition, and to allow real-time adjustment of pulsed frame rates during cases.

**Data Supporting the Use of Lower Pulsed Frame Rates**

In this issue of *Circulation: Cardiovascular Interventions*, 2 studies support the use of lower pulsed frame rates in diagnostic catheterization and coronary intervention (PCI). Pyne et al, taking advantage of a catheterization laboratory quality improvement initiative to reduce radiation, performed a retrospective review of angiographic image quality and radiation measures before and after implementation of a default digital pulse fluoroscopy and cine-acquisition rate of 10 FPS. The standard dose cohort (15 FPS) was compared with the reduced dose cohort for total x-ray dose in air kerma (mGy), fluoroscopy time, and contrast use. Overall, 1015 patients were included in the analysis and characteristics of the standard and reduced dose groups were similar for the majority of variables. About half of cases were PCI, and radial access was used in 62% of cases. Although fluoroscopy time and contrast use were similar, the mean total x-ray dose was significantly lower in the 10 FPS period (1179.1±1147.0 versus 1763.1±1388.0 mGy; P<0.0001) with a 38% lower exposure after adjustment. No difference in image quality was found by blinded review using a semiquantitative 1 to 10 scale in a subgroup of 104 patients matched for clinical and procedural variables. The study did not account for image acquisition angles, number of cine-acquisitions, or other technical factors under operator control.

A second single-center study in this issue by Agarwal et al examined radiation dose in patients undergoing elective left heart catheterization before and after a change in the default fluoroscopic frame rate from 10 to 7.5 FPS, keeping an acquisition frame rate of 10 FPS. Radiation practices were also reviewed, including recommendation for the use of less extreme angulations, maximal collimation, reduction in source to detector distance, increased field of view, and increased geometric magnification by decreasing source to object distance. Propensity matching was used to match patients in the 2 groups and by diagnostic and PCI procedures. Overall, 6094 patients (93% diagnostic procedures) were included in the analysis. For diagnostic catheterization, the median total x-ray dose was 625 versus 798 mGy (P<0.001) and for PCI 1675 versus 2463 mGy (P<0.001). The median total air kerma was significantly reduced after institution of lower fluoroscopy rates, with 22% and 32% reduction in diagnostic and interventional procedures, respectively. Similar to the study by Pyne et al, fluoroscopy times were not influenced by the change in pulsed frame rate. Tube angulation previously has been shown to be an important factor in radiation exposure. Using spatial modeling, radiation dosimetry with beam angulation was also examined in the current study. To assess the effect of angulation, fluoroscopic and acquisition sequences were categorized into tertiles based on the air kerma rate and radiation maps were created indicating red, yellow, or green zones based on percentage of images in the lowest tertile of exposure. The use of lower fluoroscopic and acquisition frame rates lowered air kerma to green and yellow zones even in steep angulation projections.

A limitation of the studies is that operator exposure was not measured. In combination, however, these studies strongly support a change in the default pulsed frame rate to a setting lower than 15 FPS. The amount of dose that is saved by changing the rate can be assessed by a medical physicist. In individual cases where image quality is considered inadequate to perform PCI, the fluoroscopy and acquisition rate can be increased for a segment or the entirety of a case.

**What About Fluoroscopy Time?**

Before the ability of x-ray systems to measure air kerma and kerma air product, fluoroscopy time was used as a surrogate for exposure. Keeping exposure time to the minimum required for a diagnosis or therapeutic intervention is certainly an important goal. Fluoroscopy time, however, is a poor measure of exposure, as in the studies discussed above, and should not be used as the sole measure of exposure. In the United States, a wide variation in fluoroscopy time was observed in >3 million procedures in the National Cardiovascular Data Registry (NCRD) Cath PCI Registry from 2005 to 2009. Although the majority of variation was...
explained by patient characteristics and procedural complexity, nearly one fifth was because of operator and hospital level factors, suggesting that radiation-reducing protocols are not standardized.\(^{16}\) The Patient’s Exposure to X-ray During Coronary Angiography and Percutaneous Transluminal Coronary Intervention (RAY\(^{\text{a}}\) ACT) study, a nationwide analysis of radiation parameters in \(\approx 34,000\) diagnostic and 28,000 PCI procedures in 2010 in France also demonstrated high variability across centers. The majority of centers registered both fluoroscopy time and kerma air product, and heterogeneity was more pronounced for kerma air product. Higher frame rate was one the factors associated with centers delivering higher radiation dose.\(^{17}\)

### Additional Parameters Affecting Radiation Exposure

Although physician training, standardized radiation protection practices, including personal shielding, and lower pulsed frame rates have a significant effect on radiation exposure, the majority of x-ray time is dictated by patient characteristics and the complexity of the procedure, which are not modifiable. Several studies have shown body mass index to be highly associated with exposure.\(^{18}\) In addition, chronic total occlusion and bifurcation PCI and number of lesions treated increase exposure to the operator than coronary procedures.\(^{20}\) This is associated with exposure.\(^{18}\) In addition, chronic total occlusion and bifurcation PCI and number of lesions treated increase exposure to the operator than coronary procedures.\(^{20}\) This is because of the higher dose per frame rate required for digital subtraction and reduction with difficulty with shielding. Data are emerging on exposure during transcather aortic valve implantation. Patient dose is approximately double PCI and average operator dose is also increased.\(^{21}\) Operator experience is also related to exposure with more experience operators having lower dose area product.\(^{18}\)

### Recommendations and Future Directions

A concerted effort from industry and catheterization laboratory staff is required to attain the lowest achievable radiation exposure for patients and operators. Companies producing catheterization laboratory equipment must be transparent about reporting dose when touting the quality of images. Physicians need to accept images produced with lower frame rates, which are adequate to accomplish the procedure but not as clear those obtained with a higher frame rate. Position statements from cardiovascular societies provide detailed recommendations on measures to reduce radiation, which should be followed and compliance monitored.\(^{5,22}\) For operators, robotic-assisted PCI has been shown to be feasible and safe, and hopefully this technology will be routinely available in our professional lifetime.\(^{23}\) Until that time, it is our responsibility to take control of radiation exposure.

### Disclosures

None.

### References


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