Relationship of Beam Angulation and Radiation Exposure in the Cardiac Catheterization Laboratory

Shikhar Agarwal, MD, MPH,* Akhil Parashar, MD,* Navkaranbir Singh Bajaj, MD,† Imran Khan, MD,‡ Imran Ahmad, MD,* Fredrick A. Heupler, Jr, MD,* Matthew Bunte, MD,* Dhruv K. Modi, MD,* E. Murat Tuzcu, MD,* Samir R. Kapadia, MD*

Cleveland, Ohio

Objectives The aim of this study was to analyze the relationship between beam angulation and air kerma in a modern cardiac catheterization laboratory.

Background Recent reports have identified the merits of reducing radiation scatter, an important determinant of radiation dose in the catheterization laboratory. Radiation scatter is poorly characterized in the context of catheterization laboratories using modern digital equipment. Understanding the principles of dosimetry may reduce the radiation exposure to patients, providers, and medical staff.

Methods Prospectively captured radiation data were extracted from a database of 1,975 diagnostic catheterizations (DCs) and 755 percutaneous coronary interventions (PCIs), which included 138,342 fluoroscopic and 35,440 acquisition (cine) sequences. Fluoroscopy and acquisition modes were categorized into tertiles based on the total air kerma measured at a standard reference point. Radiation maps were modeled according to the relative proportion of exposure in each projection.

Results Median air kerma during DCs and PCIs was 677 and 2,188 mGy, respectively. Fluoroscopy contributed to 66.3% of total dose during PCIs compared with 39.7% during DCs (p < 0.001). Fluoroscopy was more sensitive to changes in angulation with a rapid increase in total air kerma on small increases in beam angulation. Complex spatial maps were created to study the impact of angulation and other covariates on total air kerma. Besides beam angulation, body surface area was the strongest predictor of the total air kerma.

Conclusions This study uniquely describes radiation dosimetry using contemporary equipment in a real-world setting. Extreme angulations were associated with high air kerma values. Fluoroscopy compared with acquisition was more sensitive to changes in angulation, with relatively larger increases in total air kerma with small increases in steepness of the angulation. (J Am Coll Cardiol Intv 2014;7:558–66) © 2014 by the American College of Cardiology Foundation
X-rays have officially been labeled as a “carcinogen” by the World Health Organization’s International Agency for Research on Cancer, the Agency for Toxic Substances and Disease Registry of the Centers for Disease Control and Prevention, and the National Institute of Environmental Health Sciences (1–3). Over the past few decades, there has been a steady increase in the number of diagnostic and therapeutic procedures, that involve ionizing radiation, including x-rays, computed tomography, interventional radiology procedures, as well as catheterization laboratory-related diagnostic and therapeutic interventions. The modern catheterization laboratory is currently “the epicenter of contemporary medical radiological tsunami” (4). Therefore, the cardiology community bears the responsibility of minimizing radiation exposure to their patients and, also, to themselves and to their professional staff (5).

The principle of ALARA (“as low as reasonably achievable”) has been proposed by the International Commission for Radiation Protection to guide responsible radiation use (6). The factors that affect the dose in interventional procedures are generally classified as patient related, equipment related, or procedure related (5). One of the most important procedure-related factors governing the amount of radiation scattered is the beam orientation and movement (5). Although radiation mapping was developed in the past (7), high-quality data detailing the radiation dose with modern catheterization laboratory equipment in real-life patient settings do not currently exist. All modern catheterization laboratories use flat-panel detectors with digital acquisition rather than the old image-intensifier systems. Most of our understanding about the predictors and parameters of the radiation dose in the catheterization laboratory arises from these old studies that were based on older systems and were performed using phantom models. Therefore, we present an analysis of radiation dosimetry with 3-dimensional visualization models in a real-world experience with contemporary catheterization laboratory equipment.

**Methods**

**Study population.** All adult patients (older than 18 years of age) undergoing a diagnostic catheterization (DC) or percutaneous coronary intervention (PCI) at the Cleveland Clinic between January 1, 2012, and July 31, 2012, were considered for inclusion. Patients were excluded if they underwent peripheral interventions, structural heart disease interventions, or catheterization using biplane angiography. The study was approved by the Cleveland Clinic Institutional Review Board.

**Study variables.** Data were extracted from the **syngo** Dynamics using Siemens CARE (Combined Applications to Reduce Exposure) analytics software (Siemens Medical Solutions, Malvern, Pennsylvania). Although the term cine is still used in catheterization terminology, the modern digital systems are no longer cine based. The images that are acquired for storage are generally said to be captured in an acquisition mode. Fluoroscopy is simply live imaging using a lower radiation dose, which is usually not stored.

The data extracted included patient-specific variables such as age, sex, and body and surface area (BSA) along with image sequence-specific variables such as imaging mode (fluoroscopy vs. acquisition), projection angles, source-to-detector distance (SID), source-to-object distance, x-ray pulse duration, frame rate, and imaging protocol. The nomenclature for the angulation was set a priori to ensure uniformity in the data analysis. Primary angulation referred to the left anterior oblique (LAO) or right anterior oblique (RAO) projection, with negative values denoting the RAO projections. Secondary angulation referred to the cranial-caudal projection, with negative values denoting the caudal projections.

The primary outcome variable was the total air kerma rate at the interventional reference point (IRP). The IRP was defined as an imaginary point located 15 cm from the isocenter toward the source. According to the International Atomic Energy Agency, kerma (kinetic energy released in a material) is the sum of the initial kinetic energies of all charged ionizing particles liberated by uncharged ionizing particles in material of unit mass (8). The air kerma rate was defined as the ratio of air kerma at the IRP and the x-ray pulse duration (in seconds). Two parameters of dose are useful for characterizing patient and physician exposure: the air kerma at the IRP and the dose-area product (DAP). Because DAP is determined by operator behavior and by variables that are not under the operator’s control, it is challenging to identify a cutoff DAP that could be labeled as high. Although DAP may be a better measure of the patient’s stochastic risk of an adverse radiation-related event, it has been demonstrated that the correlation between DAP and the absorbed dose determined using thermoluminescent detectors is rather poor (9). Based on these reasons, we chose to use the air kerma rate at the IRP as the primary outcome variable of interest.

The equipment in our catheterization laboratory was calibrated in a standard fashion throughout the study duration. In 2012, we used a fluoroscopic frame rate of 10 frames/s, and an acquisition frame rate of 15 frames/s. For a standard pre-set angulation, each machine was calibrated to deliver 29 nGy/pulse for fluoroscopy and 170 nGy/pulse for acquisition.

**Data analysis.** Statistical analysis was performed using Stata version 12.1 (StataCorp, College Station, Texas) and

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**Abbreviations and Acronyms**

- **BSA** = body surface area
- **DAP** = dose-area product
- **DC** = diagnostic catheterization
- **IQR** = interquartile range
- **IRP** = interventional reference point
- **LAO** = left anterior oblique
- **PCI** = percutaneous coronary intervention
- **RAO** = right anterior oblique
- **SID** = source-to-detector distance

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**Note:** The full text of the document includes detailed statistical analysis and results, which are not shown here for brevity.
R version 3.0.1 (Comprehensive R Archive Network, Vienna, Austria). All continuous variables are expressed as medians with interquartile ranges (IQRs), and all categorical variables are expressed as proportions. Kruskal-Wallis and chi-square tests were used for comparison of continuous and categorical variables, respectively.

All fluoroscopic and acquisition sequences were categorized into tertiles (low, medium, and high) based on the air kerma rate. Subsequently, radiation maps were created based on the proportion of high tertile air kerma rate acquisition in each projection. In each radiation map, 3 discrete zones were identified. The red zone denotes projections where <26% of the images were procured in the lowest tertile of air kerma rate. The yellow zone denotes projections where 26% to 40% of the image procurement occurred in the lowest tertile of air kerma rate. The green zone denotes projections where >40% of the image procurement occurred in the lowest tertile of air kerma rate. All maps were created separately for fluoroscopy and acquisition modes.

**Multivariable analysis.** Multivariable linear regression analysis was performed with the logarithm-transformed air kerma rate as the dependent variable; 3-dimensional spatial maps were created separately for fluoroscopy or acquisition based on the described regression model. All patient-related and image sequence–related characteristics listed were used as covariates. SID was square root transformed to eliminate the leftward skew in its distribution. The mode of imaging (fluoroscopy vs. acquisition) was treated as an interaction variable, and all covariates were interacted with this variable.

To appropriately transform the projection angle, several different trigonometric functions were considered. However, based on the current understanding about increasing air kerma with increasing angulation, sine transformation was chosen. Linear splines were introduced at 0° for both primary and secondary angulation to incorporate asymmetry about the null.

**Results**

The baseline characteristics of the included subjects are shown in Table 1. We included 2,617 patients undergoing 2,730 procedures in the study. Of the 2,730 procedures, 1,975 (72.3%) were DCs and the remaining 755 (27.7%) were PCIs. All included procedures yielded a total of 138,342 fluoroscopic and 35,440 cine sequences. Table 2 demonstrates the comparison of total x-ray duration and total air kerma between DCs and PCIs, stratified by the imaging mode. The median x-ray duration was 428s (IQR: 260 to 745 s) and 1,382s (IQR: 910 to 2,147 s) during DCs and PCIs, respectively (p < 0.001). Similarly, the median air kerma was 677.2 mGy (IQR: 447.6 to 1,060.9 mGy) and 2,188.3 mGy (IQR: 1,356.9 to 3,565.2 mGy) during DCs and PCIs, respectively (p < 0.001). DCs and PCIs differed significantly with respect to the relative proportions of fluoroscopy versus acquisition. Acquisition contributed to 11.7% of the total x-ray duration during DCs.
compared with 6.0% of total x-ray duration during PCIs (p < 0.001). Similarly, acquisition contributed to 60.3% of the total air kerma during DCs compared with 33.7% of the total air kerma during PCIs.

Table 3 demonstrates the categorization of all fluoroscopy and acquisition sequences into tertiles (low, medium, and high) based on the air kerma rate. Figure 1 represents the scatterplot of all acquisitions that occurred in the high tertile of air kerma rate during fluoroscopy (Fig. 1A) or acquisition (Fig. 2B). The density of points in these plots provided an approximate estimation of projections that were associated with a high air kerma rate. Broadly speaking, left-sided projections appeared to be responsible for higher air kerma rates compared with right-sided projections. Similarly, caudal projections appeared to be associated with higher air kerma rates compared with the cranial projections. Figures 2 and 3 depict the systematic representation of the proportion of the various air kerma rate tertiles in each projection for fluoroscopy and acquisition, respectively. During acquisition, the proportion of low-tertile sequences in extreme projections of LAO cranial, LAO caudal, RAO cranial, and RAO caudal were 14.5%, 0%, 11.1%, and 11.8%, respectively. During fluoroscopy, the proportion of low-tertile sequences in extreme projections of LAO cranial, LAO caudal, RAO cranial, and RAO caudal were 11.7%, 11.5%, 20.6%, and 14.3%, respectively. For fluoroscopy and acquisition modes, the highest proportion of low-tertile sequences occurred during the shallow straight LAO (between 0° and 20°) projection.

Based on the proportion of the low-tertile sequences in various projections, radiation maps were created, as shown in Figure 4. For both fluoroscopy and acquisition, all extreme projections were associated with a particularly high degree of air kerma rates. In addition, LAO caudal and RAO caudal projections were responsible for the highest air kerma rates during both fluoroscopy and acquisition. However, there were few marked differences between the air kerma rates during acquisition and fluoroscopy. Careful comparisons of the 2 parts of Figure 4 demonstrate that the fluoroscopy map consists of a larger number of projections that lie in the red zone compared with the acquisition map. Second, the relative increase in the air kerma rate from the lowest to the highest values during acquisition was 3.4-fold (2.29 mGy/s in straight shallow RAO to 7.89 mGy/s in extreme LAO caudal) compared with a 4.4-fold relative increase in the air kerma rate during fluoroscopy (0.31 mGy/s in straight shallow RAO to 1.37 mGy/s in extreme LAO caudal projection). Both of these observations implied that fluoroscopy was considerably more sensitive to changes in the beam.

### Table 3. Dose Tertiles for Acquisition and Fluoroscopy

<table>
<thead>
<tr>
<th>Dose Tertiles, mGy/s</th>
<th>n</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acquisition (n = 35,440)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 3.11</td>
<td>11,814</td>
<td>Low</td>
</tr>
<tr>
<td>3.11–5.77</td>
<td>11,813</td>
<td>Medium</td>
</tr>
<tr>
<td>&gt; 5.77</td>
<td>11,813</td>
<td>High</td>
</tr>
<tr>
<td><strong>Fluoroscopy (n = 138,342)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 0.36</td>
<td>46,114</td>
<td>Low</td>
</tr>
<tr>
<td>0.36–1.35</td>
<td>46,115</td>
<td>Medium</td>
</tr>
<tr>
<td>&gt; 1.35</td>
<td>46,113</td>
<td>High</td>
</tr>
</tbody>
</table>
angulation, with a relatively larger increase in the air kerma rate with small increments in the projection angles, compared with acquisition. To determine the reasons for a rapid increase in air kerma rate with angulation during fluoroscopy, we studied the differences in x-ray tube loading parameters, namely, tube power (kW) (Fig. 4) and peak kilovoltage (kVp) (Online Fig. 1) in each projection during fluoroscopy and acquisition. Comparison of both of these parameters between fluoroscopy and acquisition revealed 2 findings. First, both x-ray tube loading parameters were significantly lower during fluoroscopy compared with acquisition. Second, there was a markedly higher variability in x-ray tube power and kVp values during fluoroscopy compared with during acquisition (Fig. 5).

Online Figure 2 demonstrates the median percentage of total fluoroscopic time (Online Fig. 2A) and total acquisition time (Online Fig. 2B) spent in each projection. Although the time proportions appeared to be evenly distributed across various projections during acquisition, there were marked differences in time-based proportions across projections during fluoroscopy. A large majority of the time spent during fluoroscopy was spent in the straight LAO projection in the red zone. Online Figure 3 demonstrates the median percentage of total fluoroscopic air kerma (Online Fig. 3A) and total acquisition air kerma (Online Fig. 3B) spent in each projection. A large majority of total air kerma during acquisition was contributed by extreme LAO caudal projections. However, the maximal proportion of the total air kerma during fluoroscopy was accumulated during exposures in the straight LAO projections in the red zone.

Multivariable modeling. Multivariable linear regression analysis based on the methodology described here was performed to construct 3-dimensional complex spatial maps for radiation and acquisition. Figure 6 along with Online Videos 1 and 2 demonstrate the complex spatial maps for fluoroscopy and acquisition, derived using the previously mentioned multivariable model at median values of all included covariates. These spatial maps clearly demonstrate the progressive increase in the total air kerma rate with an increase in the beam angulation in various directions. Besides beam angulation, the regression modeling demonstrated BSA to be the most significant predictor of total air kerma rate (Online Figs. 4 and 5, Online Videos 3 and 4).
addition, SID and magnification were other significant determinants of total air kerma rate during fluoroscopy and acquisition (Online Figs. 6 to 9).

**Discussion**

Our study investigated the parameters of radiation dose measured using air kerma in a modern cardiac catheterization laboratory. We have 3 important observations. First, fluoroscopy contributed to a significantly higher proportion of total air kerma during PCIs compared with DCs. Second, the fluoroscopic air kerma rate was more sensitive to changes in angulation compared with the acquisition air kerma rate. Third, BSA appeared to be an important secondary predictor of the total air kerma rate in addition to beam angulation.

Tube angulation has been shown to influence the amount of radiation dose to patients and operators (10–17). Although wide ranges of tube angulations are possible, only a few are actually used in the catheterization laboratory. Stenoses in each arterial segment could be studied in multiple angulations without loss of significant precision (7). Knowledge about less irradiating projections is of paramount importance in adhering to the ALARA principle and minimizing radiation exposure to patients and operators.

There is a wide variation across the literature in the estimation of the contribution of fluoroscopy to the total radiation dose during cardiac catheterization. Using average procedure times measured at our institution in 1978, the contribution of fluoroscopy to total radiation dose was estimated to be ~20% (18). The authors measured an average fluoroscopy time of 12.7 min and a cine time of 1.8 min (18). In 1997, Zorzetto et al. (19) reported that fluoroscopic contribution to total radiation dose was 30% during DCs and 52% during PCIs (19). In contrast to these experiences, the procedural times have decreased considerably, and the contribution of fluoroscopy to total radiation dose and time has increased to a much greater extent.

There is a paucity of literature evaluating the parameters of radiation in a modern catheterization laboratory. Most modern catheterization laboratories use flat-panel detectors with digital acquisition versus the old image-intensifier systems. Most of our understanding of the radiation scatter in catheterization laboratory comes from studies published using image-intensifier systems on phantom models (7). Our study is the first of its kind to

**Figure 3. Proportion of the Imaging Sequences Stratified by Tertile of Air Kerma Rate in Various Projections of Acquisition**

In each projection (represented by a cell), the relative proportions of various tertiles of imaging sequences are shown above. The **green bars** represent the lowest tertile of air kerma rate; **yellow bars** represent the medium tertile of the air kerma rate; and the **red bars** represent the highest tertile of air kerma rate. These figures were used to design the radiation maps shown in Figure 4. Abbreviations as in Figure 1.
attempt to shed light on radiation dose in real patients using modern equipment. Besides this, there is very little understanding of differences in radiation doses between fluoroscopy and acquisition. With a progressively increasing contribution of fluoroscopy to total radiation dose, it is important to understand the mechanisms by which one could reduce the absorbed dose during fluoroscopy. Fluoroscopy results in a relatively larger increase in total air kerma with small increments in the projection angles compared with the image acquisition. For example, 50% of the total fluoroscopic time was spent in the straight LAO projection, which is commonly used for movement of catheters and wires from the groin to the heart. The operators rarely pay attention to the angulation of the C-arm during this step of the procedure. Paying close attention to the angulation and placing the C-arm in the 0° to 20° angulation would result in a more than 3-fold reduction in the amount of radiation scattered during fluoroscopic acquisition.

The differences in air kerma rates between fluoroscopy and acquisition are the most novel findings of this study. We have demonstrated a significantly large relative change in air kerma rates during fluoroscopy compared with acquisition. Several factors might be responsible for this difference. First, fluoroscopy entails low-dose radiation, which is more sensitive to tissue-based attenuation. Therefore, small changes in angulation lead to considerable change in the air kerma rate during fluoroscopy. On the other hand, acquisition entails a large radiation dose delivery to obtain higher resolution images. We have demonstrated significantly higher x-ray tube loading parameters (kVp and tube power) during acquisition compared with fluoroscopy, indicating that acquisition is likely being performed at the maximal
x-ray tube-loading capacity. This implies that there is room for little variation in x-ray output with changes in beam angulation during acquisition. This observation has implications for x-ray system design in that systems could be recalibrated to use lower air kerma outputs for the more favorable projection angles. Some modern x-ray systems have the capability to decrease the detector dose per pulse during acquisition while changing video chain gain to maintain acceptable image brightness.

Our study analyzed the total air kerma measurements at the IRP. Although the total air kerma at the IRP provides a reliable measure of total dose delivered to the patient, critics might argue that there is little information about the extent of radiation exposure to the operator. However, the radiation protection for the operator cannot be treated independently from radiation protection for the patient because they are correlated. The radiation exposure for the operator is secondary to the radiation scattered from the patient. Thus, if we aim to reduce the radiation dose delivery to the patient, the radiation scattered and absorbed by the operator would be consequently reduced. Despite the correlation between the radiation exposure to the patient and the operator, the relationship is not completely straightforward. For example, Kuon et al. (7) demonstrated that caudal LAO views result in as much radiation exposure to the interventionalist as a cranial LAO view despite an increased distance of the source from the operator in caudal angulation. However, caudal angulation results in an increase in the patient’s skin entrance site from the operator position leading to a greater proportion of the scattered radiation directed toward the operator. Furthermore, the degree of tissue penetration during caudal angulations is considerably larger than the tissue penetration required during cranial angulations, contributing to higher air kerma rates during the former compared with the latter.

Our findings are in agreement with the results of Theocharopoulos et al. (20). The authors had recommended that the patient must be approached from the right-hand side rather than the left-hand side because the radiation backscatter is much reduced. In addition, they recommended a decrease in tube voltage and milliamperage to reduce patient and staff exposure to a minimum. Although most modern catheterization laboratory equipment has automatic imaging protocols to optimize image quality, it is of vital importance that the operators pay attention to radiation reduction in their respective catheterization laboratories. In addition to these measures, other good radiation practices such as the use of personal protective gear, strict beam collimation, use of pulsed fluoroscopy as well as low-dose acquisition must be used to keep the radiation doses to as low as reasonably achievable. There are several ongoing efforts to reduce radiation in the catheterization laboratory. There are live feedback systems that can help to analyze exposure to individuals for a specific case or situation. For example, Siemens Medical Solutions has developed CARE applications that provide a broad range of dose-saving applications, enhanced monitoring, and reporting of the radiation being generated (21). Robotic procedures to reduce operator radiation exposure are another important area that is being actively pursued. Change in image acquisition and processing has been the area of constant improvement to reduce radiation with acceptable image quality. It has increasingly become clearer that superior image quality at the expense of higher radiation is not necessary at all times, but enough definition in an image to accomplish a safe and effective procedure with minimal radiation is an acceptable goal.
Study strengths and limitations. To the best of our knowledge, this is the first study to characterize the parameters of radiation dose in a modern-day catheterization laboratory in a real-patient setting. We have used a large number of projections to create a statistical model with an exceptional degree of predictive ability. Unique to this analysis was separate characterization of radiation parameters of fluoroscopy versus acquisitions, given a considerably large contribution of fluoroscopy to total radiation dose and time. Because all the characteristics that were entered into the predictive model were patient or procedure related, it is possible to accurately predict the amount of air kerma at the IRP, even before stepping on the foot pedal. This could be potentially used in the creation of a “radiation protection advisor,” which may be incorporated into the catheterization laboratory equipment, guiding the operator to avoid high-radiation zones.

Besides being limited by the traditional biases of an observational study, our study has a few other limitations. As pointed out before, the total air kerma might not be completely reflective of the amount that is absorbed by the catheterization laboratory personnel. Second, the radiation absorbed by the operator is likely to be a function of the projection itself, which is not possible to incorporate into the regression model.

Conclusions

Fluoroscopy contributed to a significantly higher proportion of total air kerma during PCIs compared with DCs. The fluoroscopic air kerma rate was more sensitive to changes in angulation compared with the acquisition air kerma rate. Compared with acquisition, fluoroscopy was more sensitive to changes in angulation, with relatively larger increases in total air kerma rate with small increases in steepness of the angulation. We recommend minimization of the use of extreme angulations, whenever possible, to reduce both patient and staff exposure. Besides beam angulation, BSA was a strong predictor of the total air kerma rate on the complex spatial map developed using multivariable regression modeling.

Reprint requests and correspondence: Dr. Samir R. Kapadia, Sones Cardiac Catheterization Laboratories, Department of Cardiovascular Medicine, J2-3, Heart and Vascular Institute, Cleveland Clinic, 9500 Euclid Avenue, Cleveland, Ohio 44195. E-mail: kapadis@ccf.org.

REFERENCES


Key Words: air kerma ■ beam angulation ■ kerma rate ■ projections ■ radiation.

APPENDIX

For supplemental material, figures, and videos, please see the online version of this article.