Reduction of Radiation Exposure While Maintaining High-Quality Fluoroscopic Images During Interventional Cardiology Using Novel X-ray Tube Technology With Extra Beam Filtering

Ad den Boer, BS; Pim J. de Feyter, MD; Willy A. Hummel, MS; David Keane, MB, MRCPI; J.R.T.C. Roelandt, MD, FESC

Background Radiographic technology plays an integral role in interventional cardiology. The number of interventions continues to increase, and the associated radiation exposure to patients and personnel is of major concern. This study was undertaken to determine whether a newly developed x-ray tube deploying grid-switched pulsed fluoroscopy and extra beam filtering can achieve a reduction in radiation exposure while maintaining fluoroscopic images of high quality.

Methods and Results Three fluoroscopic techniques were compared: continuous fluoroscopy, pulsed fluoroscopy, and a newly developed high-output pulsed fluoroscopy with extra filtering. To ascertain differences in the quality of images and to determine differences in patient entrance and investigator radiation exposure, the radiated volume curve was measured to determine the required high voltage levels (kV_{peak}) for different object sizes for each fluoroscopic mode. The fluoroscopic data of 124 patient procedures were combined. The data were analyzed for radiographic projections, image intensifier field size, and x-ray tube kilovoltage levels (kV_{peak}). On the basis of this analysis, a reference procedure was constructed. The reference procedure was tested on a phantom or dummy patient by all three fluoroscopic modes. The phantom was so designed that the kilovoltage requirements for each projection were comparable to those needed for the average patient. Radiation exposure of the operator and patient was measured during each mode. The patient entrance dose was measured in air, and the operator dose was measured by 18 dosimeters on a dummy operator. Pulsed compared with continuous fluoroscopy could be performed with improved image quality at lower kilovoltages. The patient entrance dose was reduced by 21% and the operator dose by 54%. High-output pulsed fluoroscopy with extra beam filtering compared with continuous fluoroscopy improved the image quality, lowered the kilovoltage requirements, and reduced the patient entrance dose by 55% and the operator dose by 69%.

Conclusions High-output pulsed fluoroscopy with a grid-switched tube and extra filtering improves the image quality and significantly reduces both the operator dose and patient dose. (Circulation. 1994;89:2710-2714.)

Key Words • radiation • fluoroscopy

Radiation exposure is of major concern to both the public and those involved in diagnostic and therapeutic procedures. Newer catheter-based therapeutic procedures require fluoroscopy for road mapping and angiography for assessment of results and are associated with increased radiation exposure, not only to the patient but also to medical personnel. Since the number of interventional procedures continues to rise and the magnitude of the radiation exposure is increasing, efforts should be made to reduce patient and personnel doses by developing new fluoroscopic techniques. A trade-off between image quality and radiation exposure is inevitable; ideally, however, new techniques should be developed to provide optimal image quality while reducing radiation exposure to a level “as low as reasonably achievable,” the ALARA principle.

In this study, we investigated the differences between conventional continuous fluoroscopy, grid-switched pulsed fluoroscopy, and a recently developed high-output grid-switched pulsed fluoroscopic technique combined with extra beam filtering to establish which modality provided the best image quality with the lowest radiation exposure to both the patient and the investigator.

Methods

Patient Procedure

The fluoroscopic data of 124 consecutive interventional patient procedures performed in one cardiac catheterization laboratory were collected prospectively and amalgamated. The data were analyzed for the geometric gantry settings, image intensifier field size, and x-ray tube kilovoltage levels (kV_{peak}). On the basis of this analysis, a reference procedure was constructed.

Assessment of Image Quality

Image qualities of the three fluoroscopic techniques were compared over a 6-month period by five senior cardiologists by the use of a double foot switch. During the first 3 months, the foot switch provided the cardiologist with continuous or pulsed...
fluoroscopy. During the second 3 months, pulsed or high-output pulsed fluoroscopy could be selected. The functions of the foot switch were randomly alternated to avoid the routine use of either the right or left foot switch. The cardiologists were blinded to the fluoroscopic mode on each switch and were asked to select the switch that they found to provide the optimal image quality. The cumulative time in each fluoroscopic mode selected by the five cardiologists over the 6-month period was used to evaluate the image quality provided by each fluoroscopic technique.

**Phantom**

To measure the personnel dose during each of the three fluoroscopic modes, a phantom was created to simulate a patient and to produce the scattered radiation. The phantom was constructed in such a way that comparable projections in patients required equal kilovoltage levels (kV<sub>peak</sub>) during fluoroscopy. The phantom was made of polymethylmethacrylate (PMMA), known as Plexiglas or Perspex, and was 22.5 cm high, 40 cm long, and 30 cm wide. The phantom was constructed in three segments: a solid abdominal part (22.5×15×30 cm); a thoracic component with mediastinal, cardiac, and pulmonary sections; and a thoracic cage with different thicknesses. The mediastinal and cardiac sections were composed of solid PMMA (15×25×9.5 cm), and the pulmonary section was simulated by wet sponges. The thoracic cage was made of PMMA plates; the lateral parts were 1.5 cm thick, the anterior plate was 4.5 cm thick, and the posterior plate was 2.0 cm thick.

**Reference Procedure**

A reference procedure was performed at the isocenter of the phantom. The isocenter was positioned 14 cm above the tabletop, 10 cm cranial to the abdominal component of the phantom and 4 cm left from the center (Fig 1).

Three fluoroscopic techniques were compared: (1) conventional continuous technique, with a tube load of 660 W; (2) grid-switched pulsed technique with an identical tube load; and (3) a newly developed, high-output pulsed technique with a tube load of 1320 W combined with extra beam filtering. All techniques were performed with the Philips MRC grid-switched x-ray tube and an Optimus CP generator. The generator delivering the energy to the x-ray tube had a clearly defined voltage-to-current (kV/mA) relation for each fluoroscopic mode, as shown in Fig 2. During continuous fluoroscopy, the maximal tube current was 6 mA. During pulsed fluoroscopy, the maximal tube current was 200 mA and the pulse frequency was 8.3 frames per second (50/6 Hz); the pulse width was 4 milliseconds (ms), resulting in a tube current per second of 6.64 mA (8.3×4 ms×200 mA), as shown in the pulsed milliamperc curve. During the high-output modes, the pulse width was doubled and the kV/mA relation was altered in such a way that at the 70-kV<sub>peak</sub> level, a maximum tube current was reached of 13.6 mA per second (8.3×8 ms×200 mA). The x-ray dose rate settings at the 7-inch entrance field of the image intensifier were for the continuous mode, 0.53 μGy/s (60 μR/s) and for both pulsed modes, 0.019 μGy (2.1 μR) per image, which, at 8.3 images per second, is equivalent to 0.157 μGy/s (17.5 μR/s). During each fluoroscopic mode, different object sizes were measured to determine the radiation volume curves.

**Patient Entrance Dose Assessment**

Since the patient's skin is normally located 60 cm from the focal spot, the patient entrance dose rate was measured in air during the three fluoroscopic techniques with a Radcal dose tempo meter at this distance.

**Physician Dose: Corneal**

During the reference procedure on the phantom, the scattered radiation dose in air was measured at the eye level of the dummy physician by a Babylne 61A monitor.

**Physician Dose: Body**

Eighteen thermoluminescence dosimeters (TLDs) were placed on a dummy investigator to quantify the physician dose and distribution over the body. The dummy investigator was positioned at the usual work position of the physician; on the right side of the patient, the nearest part positioned 75 cm from the isocenter. The TLDs on the dummy investigator were located at six different positions: the eye, collar, thorax, groin, femur, and tibia.

**Statistical Analysis**

To study differences between the fluoroscopic techniques, Friedman's tests were carried out. Significance was stated at the .05 probability level. Wilcoxon's rank sign tests were used when two techniques were compared. Analogous to Bonferro-
Gantry Settings Used Per Image Intensifier Field in Percent

<table>
<thead>
<tr>
<th>Projection</th>
<th>9-Inch</th>
<th>7-Inch</th>
<th>5-Inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>45</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>Left anterior oblique</td>
<td>17</td>
<td>32</td>
<td>20</td>
</tr>
<tr>
<td>Right anterior oblique</td>
<td>34</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Cranial</td>
<td>5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Caudal</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Right superior oblique (RAO with cranial angulation)</td>
<td>6</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Left superior oblique (LAO with cranial angulation)</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Right inferior oblique (RAO with caudal angulation)</td>
<td>5</td>
<td>10</td>
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</tr>
<tr>
<td>Left inferior oblique (LAO with caudal angulation)</td>
<td>3</td>
<td>7</td>
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</tr>
<tr>
<td>Lateral</td>
<td>5</td>
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<tr>
<td>Others</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RAO indicates right anterior oblique; LAO, left anterior oblique.

Bonferroni's correction for repeated t tests, a more precise value of P=.02 was required for significance.

Results

Results of Patient Procedure

Gantry Settings

The total fluoroscopic time was 1711 minutes (average, 13.8 minutes): the 9-inch field was used for 291 minutes (17%), the 7-inch field, 650 minutes (38%), and the 5-inch field, 770 minutes (45%). The 9-inch field size was selected most frequently for frontal and right anterior oblique projections, whereas the 5-inch mode was selected most frequently for left anterior oblique projection. The amalgamated gantry setting data for all 124 patient procedures are presented in the Table.

Image Quality

The quality of the images during pulsed fluoroscopy was superior to those during continuous fluoroscopy as a result of a higher dose per image, a shorter pulse width, and image enhancement. The quality of the images during high-output pulsed fluoroscopy was better than the quality obtained during continuous and pulsed fluoroscopy. The high-output pulsed technique, combined with extra beam filtering, was used routinely because of its superior image quality.

Results of Reference Procedure

High Voltage Level

The voltage (kVp) level required on an x-ray tube is dependent on the technique deployed, the object size, the selected image intensifier field, and the gantry settings. The pulsed techniques permitted the performance of fluoroscopy with lower kilovoltages and the penetration of larger objects (more obese subjects). Even a transmission of 50 cm was possible at the 9-inch field. Fig 3 shows the transmission with a 7-inch image intensifier field. ANOVA shows significant difference between the three techniques. It can be seen from Fig 4 that the high-output mode without extra filtration was able to produce a maximal skin dose of 170 mGy/min (19.7 R/min), which is unacceptably high for fluoroscopy.

Patient Entrance Dose

The maximal dose rate measured during continuous fluoroscopy was 110 mGy/min. The maximal dose rate during pulsed fluoroscopy (8.3 images per second) was 87 mGy/min. During the high-output pulsed fluoroscopy, the application of an extra filter of 1 mm aluminum plus 0.4 mm copper significantly reduced the dose rate (from 170 to 53 mGy/min). The total beam filtration during the high-output mode consisted of 4.5 mm aluminum and 0.4 mm copper. Conventional continuous fluoroscopy compared with pulsed fluoroscopy (P=.08) showed a dose reduction in the higher energy ranges. Continuous compared with the new, high-output, fluoroscopy and extra filtering (P=.016) reduced the dose by 54%. Pulsed compared with the high-output pulsed technique and extra filtering (P=.016) showed a reduction of 42%.

Physician Dose: Corneal

For each fluoroscopic mode, the scattered radiation dose rates were measured at the eye level of the dummy physician, with the described phantom as a patient. The dose measured in air is shown in Fig 5. Comparison of the three techniques showed a significant difference. The pulsed technique, compared with continuous fluoroscopy, reduced the corneal radiation exposure by...
46%. When the high-output pulsed technique with extra filtration was compared with continuous fluoroscopy, the reduction in corneal radiation exposure was >69%.

Physician Dose: Body

TLDs on the dummy investigator revealed the same dose pattern for all fluoroscopic modes (Fig 6). There is a significant difference between the three techniques. Because scattering is energy dependent, the lower tube voltages used during the pulsed techniques were the primary reason of the lower personnel dose. The exposure rate to the body during pulsed fluoroscopy was 60% less than with continuous fluoroscopy. During the high-output technique with extra filtration, the body exposure was reduced by >70% compared with the continuous mode.

Radiation Exposure According to Gantry Settings

Measuring the scattered radiation as dose per procedure, it was found that >75% of personnel dose is received during fluoroscopy of left projections. Fig 7 illustrates the total scattered radiation dose per investigation and the influence of the gantry position.

Discussion

Awareness of the adverse effects of x-ray radiation exposure has been an important stimulus to reduce radiation exposure as low as reasonably achievable (ALARA). The pulsed-mode version is a newly developed technique that, primarily because of its lower pulse frequency, is associated with a much lower patient radiation exposure compared with conventional continuous fluoroscopy. The most modern version of fluoroscopy, the high-output pulse mode, causes an even greater decrease in patient and occupational exposure compared with continuous-mode fluoroscopy because of its low pulse frequency and hardening of the x-ray beam by the use of extra filters. Patient radiation exposure was further reduced when a pulse frequency of 8.3
(50/6) images per second was used instead of the usual pulse frequency of 12.5 (50/4) images per second. It appeared that the reduction of the pulse frequency to 8.5 images per second provided satisfactory fluoroscopic images in a large majority of the procedures. During an audit of 124 patient procedures, only in a few instances, primarily during imaging of fast targets such as a guide wire in the distal right coronary artery with a small image field, was the time difference between the images too long, and resetting to 12.5 images per second was required.

The phantom that we used to measure the radiation dose during different fluoroscopic modes was a specially custom-made construction. The square configuration of the phantom was different from that used in many other studies,1-7 in which a round phantom was deployed. Also, we added an abdominal component to the phantom, because the upper abdominal organs have a significant effect on x-ray scattering and therefore must be taken into account. This was not performed in previous studies,1-3,8-10 in which only anterior oblique projections were used. From previous studies in patients we obtained radiation levels measured at different projections. The phantom was specially constructed so that it accurately simulated the actual patient radiation levels during similar projections.

In our study, we clearly demonstrated that with the new high-output pulsed technique, the x-ray tube must be additionally shielded so that the x-ray exposure is maximally reduced. Our results are in agreement with previous publications1-3,11,12 that have reported a similar scattered radiation pattern around the patient, with the exception of the tibial dose, which was lower in this study. The lower tibial dose was a result of the extra shielding of the x-ray tube with lead, so that the only exposure to the tibia was scattered radiation from the patient. In addition, the x-ray tube was covered with extra lead, because the position of the lower extremities of the operator is close to the tube and the high-output modes produce more radiation leakage.

Of particular interest, this study revealed that >75% of the cardiologist radiation dose is received during fluoroscopy in left projections. This point has potential consequences for the practice of fluoroscopy during coronary interventional procedures. The use of shields between the patient and the physician would substantially prevent radiation exposure to the head and neck area.

Results of measurements not shown in this study indicated that the use of a 0.5-mm leaded glass screen reduced the head and neck area dose by 80% and the abdominal area dose by 50%.

Conclusions

The combination of high-output pulsed fluoroscopy and extra filtration produces images superior to those with current established fluoroscopic modes. Pulsed fluoroscopy allows a lower image intensifier entrance dose rate compared with continuous fluoroscopy (because of the lower frame rate). The image quality is superior and the required kilovoltages (kVpeak) on the x-ray tube are lower during both pulsed modes, and the technique allows the performance of fluoroscopy on more obese patients. The high-output, low-pulse, extra-filtered fluoroscopic technique produces excellent image qualities and reduces both patient entrance and occupational radiation dose.

References

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