Radiation Protection in CT Fluoroscopy

Ryoichi Kato, M.D.,* Kazuhiro Katada, M.D.,† Hirofumi Anno, M.D.,† Shoichi Suzuki, R.T.,† Yoshihiro Ida, R.T.,‡ and Sukehiko Koga, M.D.§

ABSTRACT

This article discusses the dose to the operator and radiation protection in computed tomographic fluoroscopy (CTF)-guided intervention. One of the major limitations of CTF is excessive radiation exposure to the operator, in particular, to his or her hands. Therefore, we developed biopsy needle-holders that permit the operator to manipulate the needle without placing his or her hands in the direct X-ray beam and evaluated the effects of using a needle-holder on dose reduction. We also measured the exposure dose to the operator’s body and evaluated the effects of using protective clothing on dose reduction. Imaging parameters were a tube voltage of 80 kVp and a tube current of 30 mA. The dose-equivalent rates for the operator’s hands and entire body were 1.150 mSv/s (H<sub>70m</sub>) and 1.60 μSv/s, respectively. When a needle-holder and protective clothing were used, the corresponding values were 0.019 mSv/s and 0.052 μSv/s. The use of a needle-holder and protective clothing is considered to be indispensable in performing nonvascular interventional radiology procedures under CTF guidance. It was confirmed that the exposure dose did not exceed the dose limit specified by the 1990 recommendation of the International Commission on Radiological Protection when adequate protective measures were taken.

Keywords: Radiation, CT, intervention

In 1976, four years after the development of X-ray computed tomography (CT), Haaga et al.¹ reported the results of their study on percutaneous biopsy under conventional CT guidance. Since that time, CT-guided interventional radiology has been widely employed as a common, routine clinical technique.²⁻¹¹ However, while X-ray fluoroscopy and ultrasonography provide real-time images, conven-

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*Japan Self Defense Force Naha Hospital, Okinawa, Japan; †Faculty of Radiological Technology, Fujita Health University School of Health Sciences, Toyoake, Aichi, Japan; ‡Division of Radiology, Fujita Health University Hospital, Toyoake, Aichi, Japan; §Department of Radiology, Fujita Health University School of Medicine, Toyoake, Aichi, Japan

Reprint requests: Dr. Kato, Faculty of Radiological Technology, Fujita Health University School of Health Sciences, 1-98 Dengakugakubo, Kutsukake-cho, Toyoake, Aichi, 470-1192, Japan

tional CT cannot permit imaging during the actual procedure. It is only possible to confirm the results of biopsy after the fact, and the procedure itself must still be performed “blind.” This lack of real-time capabilities has been a major limitation in conventional CT-guided procedures. To overcome this limitation, in 1993, Katada et al. and Kato et al. developed CT fluoroscopy (CTF) and conducted preliminary clinical studies. CTF permits CT images to be reconstructed and displayed with a reconstruction time of 0.17 seconds and a temporal resolution of 6 images per second, using a fast arithmetic unit and a partial reconstruction algorithm. As in ultrasonography, tomographic images can be observed in real time as an animated sequence. CT fluoroscopy differs from conventional cine display of CT images with regard to real-time capabilities. Under CTF guidance, the biopsy needle can be advanced to the lesion while the puncturing direction and route are observed in real time on the display screen. This makes it much easier to compensate for movement of the target lesion during the procedure, so biopsy can be performed more easily and accurately compared with conventional CT-guided biopsy techniques. Thus, CTF makes it possible to perform biopsy at any desired region, and no special training or techniques are required. Moreover, CTF-guided biopsy is possible in lesions that are difficult to evaluate using ultrasonography (e.g., due to the presence of gas or bone) or impossible to visualize by X-ray fluoroscopy.

One of the major problems of CTF, however, is excessive radiation exposure to the operator, in particular, to his or her hands, because various operations are performed within the direct X-ray beam when the interventional devices are manipulated manually. To overcome this problem, we devised biopsy needle-holders that permit the operator to manipulate the needle without placing his or her hands directly in the X-ray beam and applied them to clinical use. In this article, we evaluated the effects of using a needle-holder and radiation reductive gloves on the operator’s hand dose reduction. We also measured the dose to the operator’s body without and with X-ray protective clothes (goggles and aprons) and determined appropriate procedure times to ensure exposure within the annual effective dose equivalent limits recommended by the ICRP.

**MEASUREMENTS OF THE DOSE AT THE OPERATOR’S HANDS**

Thermoluminescent dosimeters (TLDs) (X/γ-ray ATL ring RP type for environmental use, Chiyoda Technology, Tokyo, Japan) were used to measure radiation exposure to the operator’s hands. Chiyoda Technology conducted the TLD measurements and converted the results to 70-μm dose equivalent for the skin at our request.

The needle holders are designed so that the needle is held perpendicular to the tip of the holder using a screw or a spring. All parts except for the spring are made of acrylic resin to minimize artifacts. Figure 1 shows a needle-holder A specifically designed for a modified Menghini needle (Seiko, Tochigi, Japan), measuring 115 × 95 × 30 mm. In this design, the needle is mounted at the tip of the holder with a screw clamp. Opposite the needle clamp is a grip that is parallel to the biopsy needle, giving the holder an overall L-shaped appearance. When the operator holds this grip and positions the needle within the direct beam in the fluoroscopic field, his or her hands should be 4 cm away from the beam. Figure 2 shows a needle-holder B for general use, measuring 108 × 18 × 18 mm. The needle is mounted at the tip of the holder with a screw clamp, and the operator holds the needle-holder 4 cm away from the beam. In both of the needle-holders described above, the needle is mounted with a screw.
Figure 1. (A) Needle-holder A for a modified Menghini needle. (B) The needle-holder A is held in the operator's left hand.

Figure 2. (A) Needle-holder B for general use. (B) The needle-holder B is held in the operator's right hand.
clamp, which makes it rather troublesome to mount the needle to the holder. We have further modified these designs to permit the needle to be mounted with a strong spring, measuring 130 x 60 x 30 mm (needle-holder C; Fig. 3). Therefore, the locations of the operator’s hands with and without the use of a needle-holder were estimated and dose was measured three times at two locations: within the direct beam and at 4 cm away from the direct beam, 1.5 cm above the surface of a 32-cm-diameter CT body phantom (PP-12T; Capintec Inc., Ramsey, NJ).

In this study, protective gloves with a lead equivalent of 0.03 mm (Acufex Fluoro-Shield Radiation Reduction Gloves; Acufex Microsurgical, Inc., Mansfield, MA) were also used to measure the effects of dose reduction (Fig. 4).

Based on this result, the permissible examination time was calculated to comply with the recommended annual tissue effective dose equivalent limit of 500 mSv specified by the 1990 ICRP recommendation.

MEASUREMENT OF THE DOSE AT THE OPERATOR’S BODY

A model 192X Dosimeter (Capintec Inc., Ramsey, NJ) and a Victoreen Radocon 500 ionizing chamber (Victoreen, Cleveland, OH) were used to measure the dose to the operator’s eyes, neck, chest, and abdomen. Doses were compared using a dosimeter calibrated against a national standard using a beam with the same half-value layer (3.45 mm Al) as the CT system, and dose correction was then performed. The absorbed dose was obtained using air kerma. From the data measured at various points during CTF, the dose equivalent for the operator’s body was calculated. When converting the absorbed dose to the dose equivalent, we employed the Sv/Gy conversion coefficient corresponding to an effective energy of 35 keV based on JIS Z 4332 (3-mm dose equivalent conversion coefficient = 1.31, 1-cm dose equivalent conversion coefficient = 1.28). The effective dose equivalent of nonuniform exposure to the body can be calculated from the following formula: 

\[ HE = 0.05 \ Ha + 0.33 \ Hb + 0.32 \ Hc + 0.30 \ Hm \]  

(\( Ha \): dose equivalent at the neck, \( Hb \): dose equivalent at the chest, \( Hc \): dose equivalent at the abdomen, \( Hm \): maximum dose equivalent among \( Ha \), \( Hb \), and \( Hc \)). This formula is based on...
Japanese laws. Based on this result, the permissible examination time was calculated to comply with the recommended annual effective dose equivalent limit of 50 mSv specified by the 1990 ICRP recommendation.\footnote{21}

In exposure dose measurements, it was assumed that the operator would be standing near the CT system (50 cm from the central beam). Under these conditions, the heights of the operator’s eyes, neck, chest, and abdomen were 49 cm, 38 cm, 28 cm, and −13 cm, respectively, relative to the center of rotation of the CT system, and the corresponding distances were 35 cm, 48 cm, 50 cm, and 50 cm, respectively.

The protective goggles with a lead equivalent of 0.1 mm (Toray Panorama Shield; Toray Inc., Tokyo, Japan) (Fig. 5) and the protective aprons for the neck and body with a lead equivalent of 0.25 mm (Kyokko Apron; Kasei Optonix, Odawara, Japan) (Fig. 6) were used to measure the effects of dose reduction.

**RESULTS**

**DOSE AT THE OPERATOR’S HANDS**

Hand dose was converted from the absorbed dose to 70-μm dose equivalent, which is the tissue dose equivalent for the skin (Table 1). When protective gloves were not worn within the direct beam, the dose equivalent rate was $1.150 \pm 0.036$ mSv/s (mean ± standard deviation). When gloves were worn, the value was reduced to 75%, $0.862 \pm 0.038$ mSv/s. When a needle-holder was used (with the hands 4 cm outside the beam), the dose equivalent rate was $0.024 \pm 0.000$ mSv/s without gloves, and was further reduced to 79%, $0.019 \pm 0.001$ mSv/s, with gloves. If protective gloves were not worn when a holder was used, the rate was reduced to 2.1%. When both protective gloves and a needle-holder were used, it was reduced to 1.7% compared with the case in which neither was used.

The permissible examination time was investigated with regard to hand exposure. For direct exposure, an examination time of only 435 seconds was required to reach the annual dose equivalent limit (500 mSv for the skin). This was increased to 26,300 seconds when both a needle-holder and protective gloves were used (at a point 4 cm from the beam center), and was 20,800 seconds when a holder was used but gloves were not worn.

**DOSE AT THE OPERATOR’S BODY**

The exposure doses measured at various parts of the operator’s body are shown in Table 2. With protection, the absorbed dose was reduced to 47% for the lens of the eye, 3.7% for the thyroid gland, 4.5% for the chest, and 0.6% for the gonads, compared with values measured without protection.

From the values in Table 2, the effective dose equivalent was calculated to be $1.60$ mSv/s without protective clothing and $0.052$ mSv/s with protective clothing. The maximum dose ($H$) was obtained at the abdomen when protective clothing was not worn and at the chest when protective clothing was worn. With protection, the effective dose equivalent was reduced to 3.3%. Based on this value, the permissible examination time was determined. A total time of 31,300 seconds was required to reach the annual effective dose equivalent limit (50 mSv).
without protective clothing, compared with 962,000 seconds with protective clothing. In a case of the lens of the eye (150 mSv), the permissible examination time was 87,700 seconds without protective glasses and 185,000 seconds with protective glasses.

**DISCUSSION**

The development of CTF has made it possible to observe CT images in real time, thus improving the accuracy and ease of interventional techniques that are difficult to perform under conventional CT guidance. However, occupational exposure to the operator is unavoidable due to its real-time characteristics. In particular, exposure to the operator’s hands from the direct beam has been a major problem in CTF since its introduction. The objective of our study was to evaluate the exposure dose to the operator in a new interventional method employing CTF. In addition, we also investigated whether the exposure dose to the operator could be reduced to within the dose limit recommended by the ICRP because, even though CTF has been demonstrated to be technically feasible, it will not gain widespread acceptance in clinical practice if the exposure dose exceeds the dose limit.

For CTF-guided transthoracic needle biopsy, the scanning conditions generally employed are a tube voltage of 80 kVp and tube current of 30 mA. The latter is lower than that used for general CT scanning because the total filtration is low, with a half-value layer of 3.45 mm Al, to compensate for the number of photons. Furthermore, the high sensitivity of semiconductor detectors permits scanning to be performed at a low tube current. Images for monitoring interventional procedures must provide adequate contrast between air, soft tissues, and bones, even at the low-exposure doses employed in the chest. As a result, continuous scanning for a maximum of 100 seconds is only possible at a low tube current. The exposure dose per scan is lower than that in general CT scanning.

The 1990 ICRP recommendations state that the annual effective dose equivalent limit for medical practitioners is 50 mSv. From this value, the permissible examination time, i.e., the time allowance before reaching the annual effective dose equivalent limit, was calculated to be 31,300 seconds without protective aprons. In addition, as the annual effective dose equivalent limit is 20 mSv averaged over 5 years, the allowable limit is 12,500 seconds. Furthermore, the permissible examination time for hand exposure to comply with the annual tissue dose equivalent limit (500 mSv) was found to be 435 seconds for direct exposure. In the case of the lens of the eye (150 mSv), the permissible examination time was 87,700 seconds without protective goggles. These results show that the dose equivalent limit for the hand is the most severe constraint.

In our previous study, the mean duration of CTF in 10 transthoracic needle biopsies without the needle holders was 82 ± 97 (standard deviation) seconds (range: 12–368 seconds). Therefore, if the operator’s hand is exposed to the direct beam, the operator would be limited to performing only 5 CTF-guided procedures per year. Therefore, the dose reduction of the operator’s hands is indispensable at CTF.

In CT studies, the X-ray beam is precisely collimated, and the exposure dose is dramatically reduced when the object is moved out of the direct beam. Thus, the exposure dose to the operator’s hands can be reduced by using a special instrument holder that allows the operator’s hands to be moved out of the direct beam. Several types of holders have been designed for X-ray fluoroscopy, but most are made of metal, which results in the generation of strong streak artifacts during CT scanning. To

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**Table 1. 70-μm Dose Equivalent of the Operator’s Hands**

<table>
<thead>
<tr>
<th></th>
<th>Without Protective Gloves</th>
<th>Using Protective Gloves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within the direct beam</td>
<td>1.150 ± 0.036</td>
<td>0.862 ± 0.038</td>
</tr>
<tr>
<td>4 cm outside the beam</td>
<td>0.024 ± 0.000</td>
<td>0.019 ± 0.001</td>
</tr>
</tbody>
</table>

80 kV (HVL 3.45 mm Al, 35 keV)

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**Table 2. The Dose Equivalent of the Operator’s Body**

<table>
<thead>
<tr>
<th></th>
<th>Without Protection</th>
<th>With Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes</td>
<td>1.71 ± 0.01</td>
<td>0.81 ± 0.01</td>
</tr>
<tr>
<td>Neck</td>
<td>1.34 ± 0.02</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>Chest</td>
<td>1.51 ± 0.01</td>
<td>0.07 ± 0.02</td>
</tr>
<tr>
<td>Abdomen</td>
<td>1.67 ± 0.01</td>
<td>0.01 ± 0.00</td>
</tr>
</tbody>
</table>

80 kV (HVL 3.45 mm Al, 35 keV)
overcome this problem, we have developed acrylic holders which generate virtually no artifacts (Fig. 7). By using any of the three holders we have designed, the operator’s hands are positioned more than 4 cm from the direct beam, and are thus only exposed to scattered X-rays. The tissue dose equivalent to the operator’s hands is reduced to 0.024 mSv/s (2.1%) from 1.15 mSv/s. In addition, the dose can be further reduced by approximately 20% by wearing protective gloves. When both protective gloves and a needle-holder were used, it was reduced to 0.019 mSv/s. In the previous study, the mean duration of CTF in 10 transthoracic needle biopsies using the needle-holders was 59 ± 59 seconds (range: 18–224 seconds). Therefore, using a needle-holder and protective gloves, the physician could perform 450 procedures without exceeding the dose limit. This seems to be a reasonable limitation in actual clinical practice. Therefore, the use of a needle-holder and protective gloves is considered effective for minimizing physician’s occupational hand exposure and indispensable in CTF-guided procedures.

In conventional CT-guided procedures, the operator receives tactile feedback from the resistance of the needle, but when a needle-holder is used, this feedback might be expected to be reduced, and manipulation of the needle might become somewhat more difficult. Since the success rate for the biopsy procedures performed using a needle-holder in the 10 cases in the previous study was 100%, the instrument was considered to be useful in actual clinical applications. Moreover, no significant differences were found in the duration of CTF scanning between procedures performed using a needle-holder and those performed without a needle-holder. This is presumably due to the large standard deviation resulting from significant differences from case to case, since the duration of CTF scanning is strongly influenced by various factors such as the size and location of the lesion, the patient’s response, the breath-holding time, the operator’s skill, and so on. However, the possible disadvantages with regard to manipulation are more than compensated for by the great advantage of being able to monitor the procedure in real time, which is impossible under conventional CT guidance.

As regards to the exposure to the operator’s body, the effective dose equivalent is 1.60 μSv/s without protection. A total time of 31,300 seconds was required to reach the annual effective dose equivalent limit, which is much less than the limit for hand exposure. However, as the effective dose equivalent was reduced to 3.3% with protection, the operator should wear the protective aprons.

In this article, the exposure dose was measured only at a tube voltage of 80 kV and a tube current of 30 mA. However, these scanning conditions need to be set higher for procedures in the abdomen, and further studies should be carried out to measure the dose under such conditions. Furthermore, in this article, the dose was measured under the conditions of 1 second per rotation and a temporal resolution of 6 images per second, but some recently developed CT scanners offer 0.5-second rotation scanning. In this case, the temporal resolution is doubled, but the tube current must also be doubled in order to maintain the same image quality. In other words, the temporal resolution of the system and the exposure dose are directly related. The rotation speed of future CT scanners is expected to increase, which will be associated with an increase in the operator’s and patient’s dose. Therefore, we need to determine the temporal resolution required for each type of procedure in the future.

**CONCLUSION**

In this article, we measured the dose of radiation to the operator during CTF. We also investigated the use of a needle-holder and protective goggles and aprons to reduce the exposure dose, and confirmed their effectiveness. These protective measures are considered to be indispensable in per-
forming nonvascular interventional procedures under CTF guidance. It was confirmed that the dose did not exceed the dose limit specified by the ICRP when adequate protective measures were taken.

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