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Percent Depth Dose (PDD) and Tissue-Air Ratio (TAR) Measurements Using an Acrylic Phantom and 3D-Printed Ion Chamber Holders

Weiyuan Wang, Ph.D., DABR, Claire Tran, MS
University of Oklahoma Health Sciences Center

ABSTRACT

This study aimed to generate system-specific Percent Depth Dose (PDD) and Tissue-Air Ratio (TAR) curves using an acrylic slab phantom and custom 3D-printed ion-chamber holders.

Ion-chamber holders were designed to hold the Radcal 10X5-6 ion chamber and 10A96 adapter. It was 3D printed using PLA filament. Two phantom holders with infill densities of 15% and 50% (masses: 509 g and 1216 g, respectively) were printed. The phantom consisted of eight acrylic slabs, each measuring 251 mm × 251 mm × 25 mm. The ion-chamber inside a phantom holder was positioned at depths from 0 to 20 cm in 2.5-cm increments.

For each depth, exposures were measured at nine tube potentials (60–140 kVp). Both infill-density holders were used for all measurements. In-air exposure and half-value layer (HVL) measurements were also performed for the nine kVp settings. All measurements were acquired in a radiographic room with a source-to-image distance (SID) of 40 in (101.6 cm), and the beam was collimated to the top surface of the phantom.

Relative to the 15%-infill holder, the 50%-infill holder produced higher measured exposures with an average difference below 4%. PDD curves were generated for depths from 0 to 20 cm at each kVp. Linear attenuation coefficients derived from the PDD data ranged from 0.215 cm^{-1} at 60 kVp to 0.155 cm^{-1} at 140 kVp. The corresponding HVLs for each kVp were also estimated. TAR curves (exposure in phantom relative to exposure in air) were also determined. For a given depth, TAR increased with kVp, whereas for a fixed kVp, TAR decreased with increasing depth.

PDD and TAR curves were successfully obtained using 3D-printed ion-chamber holders and an acrylic phantom. These datasets will support future system specific fetal and organ dose estimation efforts.

CONTACT

Weiyuan Wang, Ph.D., DABR
Department of Radiological Sciences
University of Oklahoma Health Sciences Center
940 NE 13th Street
Garrison Tower, Room 3254
Oklahoma City, OK 73104
Office: (405) 271-8001 Ext 35419
Email: Weiyuan-Wang@ouhsc.edu
Cell: (405) 596-2862
Fax: (405) 271-3462

INTRODUCTION

To estimate fetal or organ radiation dose from diagnostic X-ray procedures, such as radiographic and fluoroscopic examinations, the Percent Depth Dose (PDD) and Tissue-Air Ratio (TAR) methods are commonly used. These methods rely on tabulated PDD and TAR factors corresponding to various depths, tube potentials (kVp), half-value layers (HVLs), and field sizes. Because the actual patient-specific imaging parameters often differ from the values available in the tables, interpolation and, in some cases, extrapolation are required to obtain dose estimates for a given examination. This study aimed to develop system-specific PDD and TAR curves using an acrylic slab phantom and custom-designed 3D-printed ionization chamber holders. The proposed approach enables rapid generation of PDD and TAR curves for individual radiographic or fluoroscopic systems, providing a practical method for estimating fetal and organ doses based on the characteristics of a specific diagnostic X-ray system.

METHODS AND MATERIALS

To establish the PDD and TAR curves, an acrylic slab phantom was used, with a Radcal ionization chamber positioned at various depths within the phantom to measure exposure at different locations inside and on the surface of the acrylic material. To accurately position the ionization chamber at multiple depths, custom chamber holders were designed and fabricated using 3D printing. The dimensions of the holders were matched to those of the acrylic slabs, allowing seamless integration into the phantom while maintaining the desired measurement geometry.

The ion-chamber holders were specifically designed to accommodate a Radcal 10X5-6 ionization chamber and a 10A96 adapter. The holders were manufactured using polylactic acid (PLA) filament with a 3D printer. Figure 1 illustrates the design and fabricated holder used in this study.

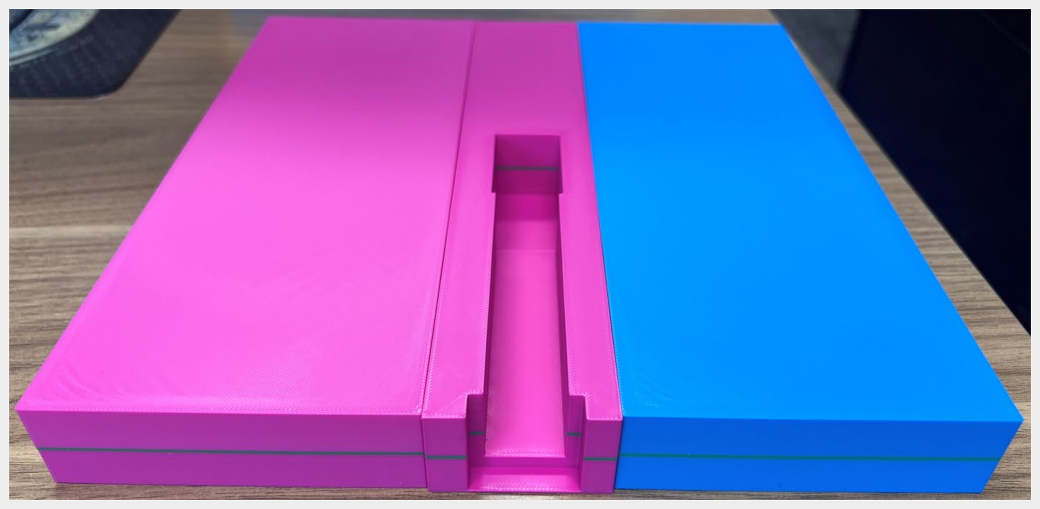

Figure 1. 3D Printed Ion-Chamber Holder

Two phantom chamber holders with infill densities of 15% and 50% were fabricated using 3D printing to evaluate the effect of holder density on scattered radiation. The corresponding masses of the holders were 509 g and 1,216 g, respectively. Each chamber holder measured 251 mm × 251 mm × 30 mm. The acrylic slab phantom consisted of eight acrylic slabs, each measuring 251 mm × 251 mm × 25 mm.

The ionization chamber, housed within the custom chamber holder, was positioned at depths ranging from 0 to 20 cm in 2.5-cm increments. Figure 2 illustrates the experiment setup with the chamber holder placed on the Acrylic phantom.

Exposure measurements were acquired at each depth using nine tube potential settings ranging from 60 to 140 kVp. Both the 15% and 50% infill-density holders were used throughout the measurements. In-air exposure and half-value layer (HVL) measurements were also obtained for all nine kVp settings.

All measurements were performed in a radiographic room with a source-to-image distance (SID) of 40 in (101.6 cm). The X-ray beam was collimated to match the top surface area of the phantom during all acquisitions.

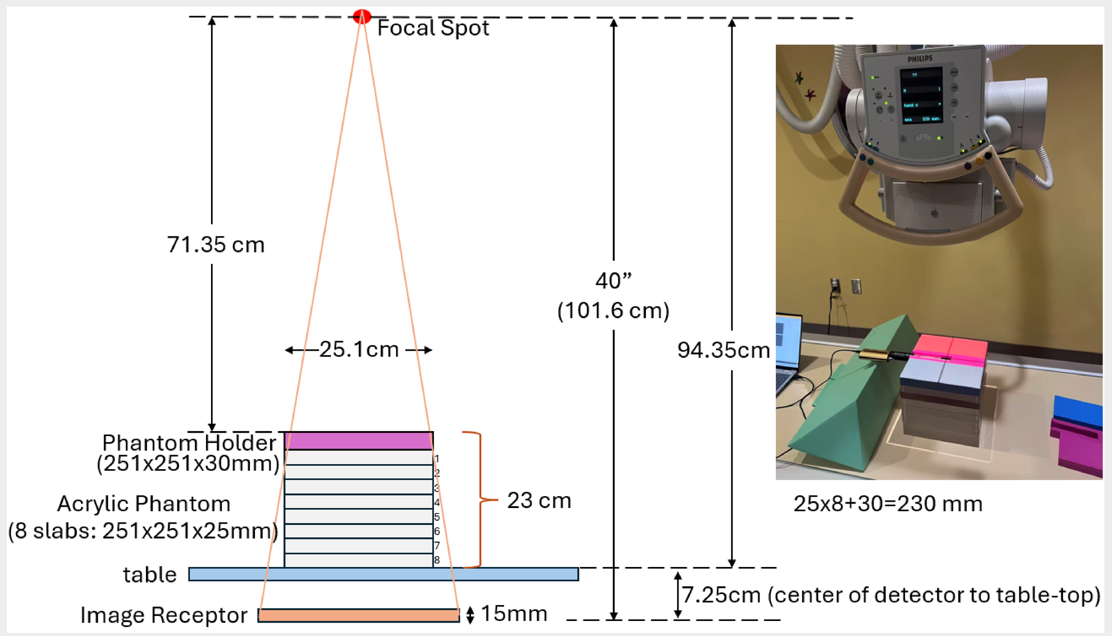

Figure 2. Experiment setup

RESULTS

Relative to the 15% infill holder, the 50% infill holder produced consistently higher exposure measurements, with an average increase of less than 4% across the evaluated tube potentials. As shown in Figure 3, the difference increased gradually with increasing kVp, ranging from approximately 0.6% at 60 kVp to 3.8% at 140 kVp.

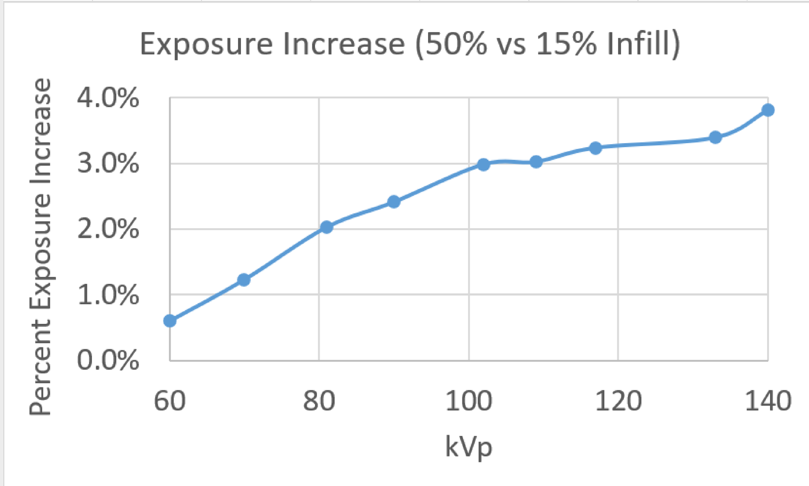

Figure 3. Exposure Increase (50% vs 15% infill)

These results suggest that increasing the infill density of the chamber holder provides a modest improvement in dose estimation by more closely replicating the scatter conditions within the phantom. However, the effect of holder density was relatively small, indicating that the majority of scattered radiation originated from the 20-cm-thick acrylic phantom rather than from the chamber holder itself. This is expected because the chamber holder was only 3 cm thick, whereas the surrounding acrylic phantom contributed up to 20 cm of scattering material. Consequently, the holder represented only a small fraction of the total scattering volume. While a higher infill density may improve measurement accuracy, its overall impact on the derived PDD and TAR values is limited compared with the influence of the acrylic phantom.

PDD curves for depths ranging from 0 to 20 cm were generated for each tube potential and are shown in Figure 4. As expected, PDD decreased exponentially with increasing depth due to photon attenuation within the acrylic phantom. For a given depth, higher-kVp beams exhibited greater penetration and therefore higher PDD values than lower-kVp beams.

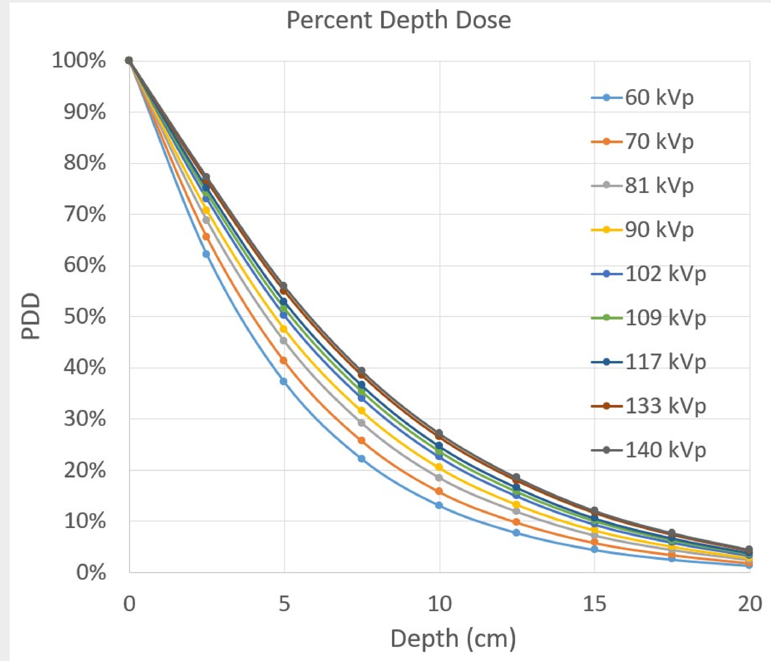

Figure 4. Measured Percent Depth Dose (PDD) Curves as a Function of Depth and Tube Potential (60 to 140 kVp).

For example, at a depth of 10 cm, the PDD increased from approximately 13% at 60 kVp to about 27% at 140 kVp. Linear attenuation coefficients derived from the PDD data decreased with increasing beam energy, ranging from 0.215 cm^{-1} at 60 kVp to 0.155 cm^{-1} at 140 kVp, reflecting the greater penetrating power of higher-energy X-ray beams. Corresponding half-value layers (HVLs) were also estimated for each kVp from the attenuation data.

Figure 5 shows the Tissue-Air Ratio (TAR) curves, calculated as the ratio of exposure measured within the phantom to the corresponding exposure measured in air.

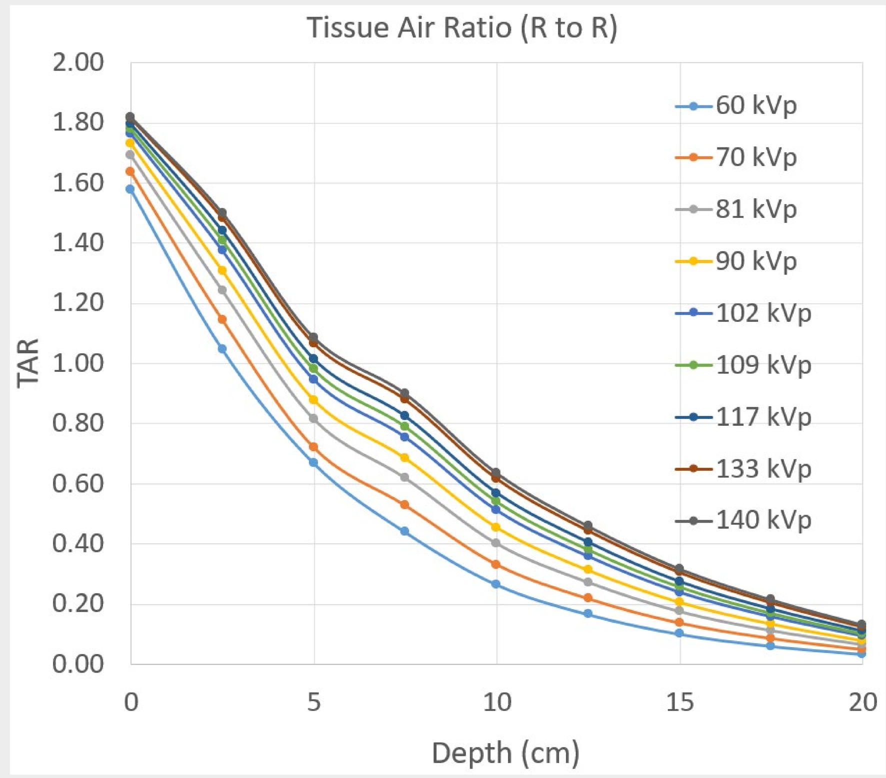

Figure 5. Measured Tissue-Air Ratio Curves (Roentgen to Roentgen) as a Function of Depth and Tube Potential (60 to 140 kVp).

The TAR values demonstrated trends consistent with the PDD results. For a given depth, TAR increased with increasing kVp because higher-energy beams undergo less attenuation and contribute more primary and scattered radiation at depth. Conversely, for a fixed kVp, TAR decreased with increasing depth due to attenuation within the phantom. The TAR curves exhibited a gradual decline with depth, with the highest TAR values observed at the phantom surface and the lowest values at 20 cm depth. For example, at 20 cm depth, TAR values ranged from approximately 0.03 at 60 kVp to 0.13 at 140 kVp, illustrating the substantial effect of beam quality on dose deposition at greater depths. These system-specific PDD and TAR curves provide a practical basis for estimating fetal and organ doses for procedures performed on the measured X-ray system.

CONCLUSIONS

PDD and TAR curves were successfully obtained using 3D-printed ion-chamber holders and an acrylic phantom. These datasets will support future system specific fetal and organ dose estimation efforts.