Contents lists available at
Journal of Association of Radiographers of Nigeria
Journal homepage: www.jarn-xray.org

Adapting the CDRH Abdominal Phantom for Dose-image Quality Optimisation in Abdominal Radiography

Nneoyi O. Egbe and Peter F. Sharp
Department of Biomedical Physics & bioengineering, University of Aberdeen, Foresterhill, AB25 2ZD, Aberdeen Scotland, UK

Permanent address:
Department of Radiography, University of Calabar, PMB 1115, Calabar, Nigeria.
E-mail: nneoyiegbe@yahoo.com

ARTICLE INFO

Article history
Received, 2007
Received in revised form, 2007
Accepted, 2007
Available online, 2007

Keywords:
X-ray, phantom, abdomen, imaging, patient equivalence, dose, optical density

Abstract

To evaluate medical X-ray doses and image quality, so called phantoms that mimic particular aspects of the patient are used. The Centre for Devices and Radiological Health (CDRH) had designed a phantom for studying radiation exposure to the human abdomen. An abdominal phantom for image quality studies has not been found in the literature. Direct comparison of the CDRH phantom performance with clinical abdominal images has not been reported previously. This study applied the phantom to conventional radiography imaging of the abdomen to establish its patient equivalence and therefore its applicability in quality control studies in radiology departments. Results show a difference in beam transmission (BT) of 21.2% ($r = 0.3$; $p>0.05$) and an optical density (OD) of 1.62 against 1.65 for patient abdominal films ($p=0.54$). Despite the variations and a poor linearity with patient data, the phantom satisfied Optical density requirements, is portable, adjustable, and simple to assemble. It can therefore find application in image quality studies in diagnostic radiology.

Introduction

The effects of ionizing radiation rule out the use of human subjects for studies involving direct exposure to radiation, but have stimulated the search for substitutes, with results that can be applied to human patients with limited error. Commercially available phantoms are expensive. Availability of more affordable and easy to use phantoms will increase their use in the radiology clinic.

Phantoms have been developed for abdominal dose studies. These include the Centre for Devices and Radiological Health (CDRH) and the American National Standards Institute (ANSI) abdominal phantoms [1]. These have been used for studying patient exposures, but there is no direct reference to their use in studying image quality. The work of Conway et al.[2] reports adjustments in material thickness to achieve good spectral matching and a design that matched the narrow beam attenuation of the tissue thickness. They also reported good accuracy for all photon energies in the diagnostic range (20 – 150 keV).

The phantom simulates the abdomen of an average patient with thickness 21.5 cm (AP) for a particular x-ray unit. Its optical density has given some indication of its possible use in image quality studies for the abdomen and lumbosacral spine, though actual tests have not been reported. Dell [3] reported patient equivalency in clinical trials over a wide variety of systems. In all these, there was no report of the utility off the phantom in image studies.

The constant need for quality control and assurance demands the availability of phantoms for performance studies of equipment and studies of the consistency of procedures. This study attempts to close the gap created by the absence of an appropriate phantom for image quality studies in abdominal radiography by applying the CDRH abdominal phantom to radiological image assessment in film screen radiography (FSR). This paper reports the series of steps that were followed to achieve a relatively patient equivalent phantom for radiography of the abdomen.

Materials and Methods

The study was conducted in three parts. The first was dose monitoring and acquisition of patient data from exposures and film densitometry. The second was the application of the patient information obtained in developing a phantom with the radiographic parameters of the patient. The final step involved performance of necessary correction measures to obtain phantom properties as close as possible to the average patient data in the study. These steps are described in the following sections.

Methodology for abdominal phantom development

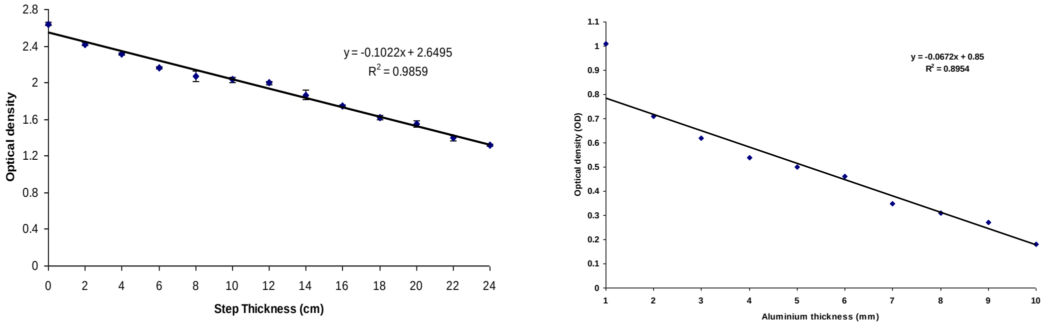
Initial exposures were made with the phantom using the average radiographic exposure data from the examination of human subjects monitored during abdominal radiography examination. Patient thicknesses were measured with a tape and the average patient thickness of the studied population determined. Lithium Fluoride Thermoluminescent dosemeters (LiF TLD-100) chips, measuring 3.2 mm x 3.2 mm x 0.9 mm, from Harshaw Chemical Co, and calibrated with known doses of x-rays monitored with a type 511 UNFORS® ionisation chamber with calibration traceable to national standards in the UK, were used to monitor patient doses. Four chips (in radiolucent plastic bags) were positioned on each patient lying in the supine position. A further three pairs of TLD chips were positioned on the side of the patient nearest the cassette to measure the percentage of the entrance dose transmitted through the each patient. Transmitted values were determined from the average of doses recorded at the upper right quadrant, lower left quadrant and between lumbar vertebrae 3 and 4 in the mid-line (spinal area).

Optical density (OD) measurements were made from plain abdominal radiographs resulting from the patient exposures. Measurements were made at soft tissue areas to include the liver area, kidney area, as well as the spine, but outside the portions with bowel gas shadows. ODs were averaged over all soft tissue areas and the spinal region to obtain mean values for comparison with corresponding parts of the phantom. Data from patient measurements were related to the tissue substitutes used in phantom construction – perspex and aluminium by comparing beam transmission through different thicknesses of the materials.

Using a calibrated perspex/acrylic step wedge, and an x-ray exposure at 75 kVp, a density/thickness curve was obtained (the step wedge was constructed in steps 2 cm to 24 cm). The exposure used was drawn from the mean value of factors used for abdominal radiography of the patients in the study. These were 75.3 (70 – 85 kVp) and 40.0 (5.8 – 180 mAs), respectively. A calibration curve was obtained (Figure 1a) from which the step heights wedges that produced the range of soft tissue densities (1.22 – 2.1) obtained from the abdominal films was determined. The appropriate thickness of acrylic required to produce an OD value equal to the mean OD measured on soft tissue abdominal radiographs of patients was thus determined.

To obtain the aluminium thickness required for the spinal area of the abdominal phantom, e aluminium step wedge was exposed above an arrangement of acrylic sheets. Varying the acrylic sheets allowed for the determination of the appropriate thickness of acrylic to be added in other to obtain the mean spinal area ODs (0.51, from the radiographs). The plot of the values of OD against aluminium thickness (Figure 1b) was used to determine the required aluminium thickness.

To set up the phantom, a number of acrylic sheets were stacked together to obtain the required thickness. The aluminium piece was set in a groove on the last sheet and the additional acrylic thickness required needed to complete the spinal requirements attached to the midline of the topmost sheet. This set-up was exposed to x-rays to determine the quality of match of the radiographic density and beam transmission with the patient data obtained in this study.



(a) **(b)**

Figure 1: Plot of step thickness and optical density produced with current abdominal exposure for (a) perspex (acrylic) and (b) aluminium.

Results

The mean thickness of the 34 patients selected for the study was 21.7 cm. A mean OD value of 1.65 (range 1.22 to 2.10) was recorded. Results of other measurements are in Table 1.

From Figure 1(a), the mean value of patient OD (1.65) was be obtained with an acrylic thickness of between 16 and 18 cm. Similarly, the OD value obtained for the spinal area in patient films (0.51) was obtained with an aluminium thickness of between 4 and 5 cm (Figure 1b). By trial and error, and by varying the thicknesses of the respective materials within the range of interest, an acrylic thickness of 17.5 cm with an additional 2.4 cm piece for the spinal area, and an aluminium thickness of 4.8 mm were found to produce the mean OD values obtained for patient films with an accuracy of ± 6.5% for soft tissue and ±13.3% for the spine.

The outcome of the process was a 17.5 cm thick arrangement of acrylic sheets with a 2.4 cm by 5 cm wide riser added to the upper sheet, in the midline of the phantom and directly above the aluminium piece at the bottom acrylic sheet, to give the beam attenuation of the spine. The phantom was built with the length and width dimensions of 25 cm by 25 cm. Results of all measurements made for patients and from the phantom are shown in Table 1.

Table 1: Mean values obtained for OD, beam transmission, total thicknesses of patient and phantom and ESD (mGy) obtained.

Medium	OD_{ST}(SD)	BT_{ST}(SD) %	OD_{SP}	BT_{SP} %	+Thickness (SD) (cm)	ESD (mGy)
Patient	1.65(0.2)	19.3 (13.4)	0.51 (0.03)	7.6 (3.9)	21.7 (0.28)	3.77(3.5)
Phantom (1)	1.71(0.06)	30.1(15.3)	0.57 (0.05)	16.7(8.8)	19.9	4.01
Phantom (2)	1.62(0.2)	23.7(9.0)	0.53 (0.04)	12.8(3.9)	20.4	4.01

OD is the optical density. ST = soft tissue, and SP = spine; BT is Beam transmission.
+ Patient thickness measured in AP projection
Phantom (1) and (2) indicate phantom before and after adjustment for optical density, respectively.

The results of radiographic tests for the phantom (Phantom 1) show differences in OD of the soft tissue area for patients and phantom. These differences were however, not statistically significant ($p = 0.10$). OD in the spinal area was statistically different ($p < 0.05$). The mean transmitted beam for the phantom was about 35.8% higher than the mean value obtained for patients, when the same exposure factors recorded for the patients were applied in irradiating the phantom. This difference was significant ($p = 0.003$). Both OD and beam transmission (BT) in the spine were statistically significantly different for patients and phantom 1 ($p < 0.05$).

Large variations were observed in beam transmission between patients in both soft tissue and spine. The effect of kVp variation and variation in patient thickness may be contributors to these large discrepancies. The range of kVps used was 70 – 85 with mAs values in the range 58 - 180. Beam transmission by the phantom was primarily dependent on the kVp/exposure used since other variables like thickness, and inherent patient characteristics did not apply to the phantom. Variations in patient measurement may be from the combined differences introduced by exposure factors and individual patient characteristics.

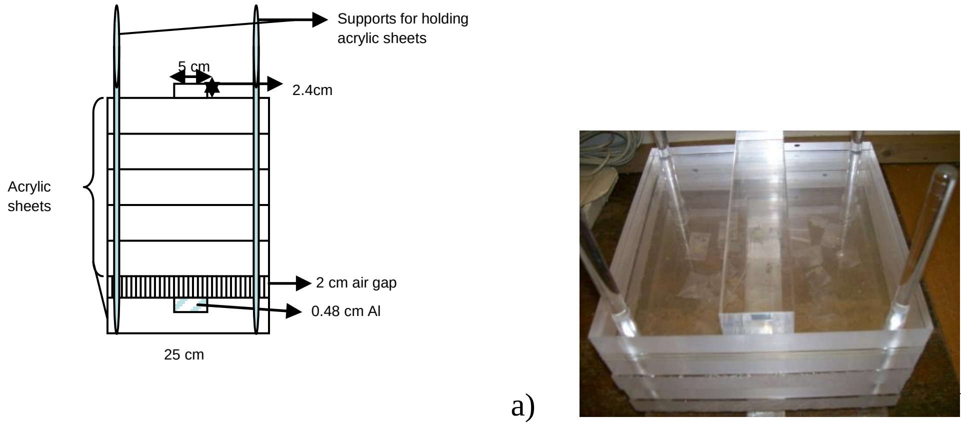
The entrance surface dose (ESD) recorded for the phantom was 4.01 ± 3.64 mGy against 3.77 ± 3.51 mGy for the patients. The difference could be attributed to production of a greater quantity of backscatter at the perspex material surface.

Adjustment and evaluation of abdominal phantom

The wide difference in the measured radiographic parameters suggested the need for some remedial measures to better align the phantom with patient radiographic parameters. To do this, it was necessary to correct for the OD and transmission intensity difference between the patients and the phantom. The phantom thickness was adjusted by changing sequentially the number and therefore, thickness of perspex sheets employed. By trial and error, 1.5 cm thickness of acrylic was removed and an air gap of 2 cm, introduced. The gap was created between the last (bottom) two sheets using spacers of appropriate size to increase the absorption of the secondary radiation and therefore lower the intensity of scatter radiation in the exit beam. The optical densities produced with this arrangement were compared with the patient abdominal films together with other measured radiographic parameters, using the 2-sample t-statistic and the Pearson's linear correlation coefficient. The existence of linear relationship between the phantom results and patient data was assessed over the entire range of exposure factors recorded during patient examination.

Results of adjustment and evaluation of the final phantom

The above corrective measures reduced the difference in transmission of the beam to 21.2% and the optical density to 1.62 (phantom 2 in Table 1). Including the 2.4 cm acrylic thickness for the spinal region, the total thickness of acrylic in the final phantom was 18.4 while the overall phantom thickness was 20.4 cm (with the 2.0 cm air gap). The final phantom, which weighed 13 kg, is shown in Figure 2b.



a) b)

Figure 2: Structural layout and image of the final abdominal phantom

Figure 3 compares the mean values of the measured parameters for patients and the phantom in the respective areas. Statistical analysis showed that OD differences between phantom 2 and patient data was not significant, with a better probability value ($p = 0.54$) than phantom 1 (0.10). Beam transmission in the soft tissue area was also not significant ($p = 0.12$), an evidence of the significant improvement from phantom 1. Values of OD and beam transmission for the spinal region of the original abdominal phantom (phantom 1) were higher than patient film values. Through the correction process described above, these were lowered. Despite this, the beam transmission through the phantom spinal area showed a statistically significant difference with patient measurements ($p = 0.02$) and the difference in spinal OD was also statistically significant ($p < 0.05$).

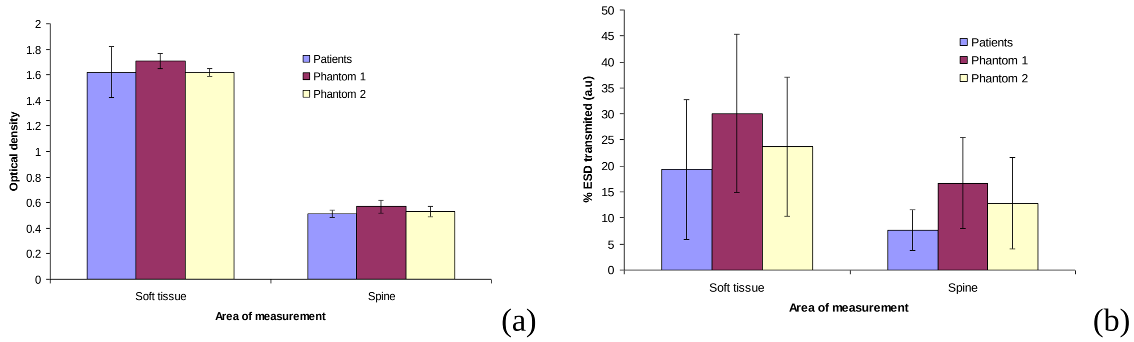


Figure 3: Comparison of (a) OD and (b) beam transmission values for patient and the phantom (1) before correction and phantom (2) after correction.

The final phantom showed no statistical difference in ESD with patient data ($p = 0.75$). The Pearson's linear correlation test for the variables between phantom 2 and patients revealed a strong positive correlation ($r = 0.9$, $p < 0.05$) in ESD. Weak and statistically insignificant positive correlation was found for the optical densities ($r = 0.4$, $p > 0.05$) and beam transmission ($r = 0.3$, $p > 0.05$).

Discussion

An imaging phantom is meant to evaluate the capability of an imaging system to demonstrate sufficiently for diagnostic purposes abnormal densities against the normal anatomical background, within the part of the body being imaged. The threshold visibility of the image details is a function of shape, physical dimensions, radiation absorption and scattering properties of the normal/abnormal tissue, against the background of the surrounding tissue[1] .

The reports of Dell [3] Conway et al. [2] and the ICRU [1] on available abdominal phantoms showed some differences in specifications. Notable differences were reported phantom thickness for different x-ray systems by Conway et al. [2]. Although these differences were in most cases negligible, experience in producing a custom made design would be invaluable and would afford an opportunity to compare results with these commercial products. In addition, the process provided an opportunity to assess the actual cost of making a simple, reproducible phantom that could be utilized in small radiology departments at minimal costs. A highly affordable phantom with appropriate x-ray characteristics would find easy application in small clinical departments. This would also encourage QA studies applying phantoms of this nature, especially because there are few abdominal studies found in literature.

Findings from measurements of radiographic parameters (OD and beam transmission) reported in the results reveal that there were no statistically significant differences in the parameters essential for adopting the phantom in radiological studies. This does not imply equality in the measured quantities. The possible addition to this section would be the effects of the increased internal scattering due to the greater thickness of perspex.

The significant differences ($p < 0.05$) noticed between the spinal regions of the patient and phantom can be related to the characteristic properties of the materials found in these areas, aluminium (in the phantom) and calcium (in bone). At the low photon energies, and especially following beam attenuation by the overlying organs (in the body) or sheets of perspex (in the phantom), calcium in the bone with a higher attenuation coefficient than Al would more effectively reduce the beam than would aluminium in the phantom. Thus a greater portion of the beam is transmitted by Al (phantom). Moreover, aluminium's energy dependence makes it a poor material for image quality related studies [4,5]. For the purpose of this study however, it was convenient to use aluminium to simulate the beam interaction in the human spinal region.

The phantom design in this study was adapted from and is based on a combination of methods described in the literature [1-3]. In the end, the phantom produced was practically based on radiodiagnostic properties of optical density and contrast resulting from beam transmission through the medium. Its design differed from the specifications in literature in the inclusion of the air gap and the thickness of aluminium used. While 0.48 cm was used in the current study, a thickness of 0.46 cm is reported in literature [1,3]. The thickness of the phantom in this study differs from the value given in literature by about 5.1%. This difference may be due to the fact that the selection process in this study was open to all adult patients. The wide range of patient thicknesses may therefore limit the applicability of this phantom to a different population. This may suggest that the resultant phantom is different from the 'standard man' CDRH phantom. It however offers a protocol for developing population specific phantoms. The construction of the phantom to allow for easy alteration of its thickness makes room for adjustments where necessary. Drawing from the above, the definition of population specific phantoms or even disease specific phantoms is supported and this may more closely approximate clinical conditions.

Conclusion

Differences are expected in study populations from place to place. In particular, abdominal volumes differ among patients within the same population due to different muscle-to-fat ratios and ileum sizes [2]. The abdominal phantom developed from specifications in literature required some adjustments to match the radiographic parameters of the patient population in the current work. Following the correction, an abdominal phantom matching the transmission and OD properties observed in the study population was obtained. The phantom demonstrated a linear but unequal relationship with the human abdominal x-ray images. It can therefore be used for perceptibility studies involving the soft tissues. Further correction may be required to obtain appropriate radiographic parameters for the spinal region for which significant differences were observed in this study.

Acknowledgement
This work would not have been possible without the help of the Biomedical Physics workshop of the Department of Biomedical Physics and Bioengineering, University of Aberdeen, Foresterhill, where all machining and other necessary technical input was made. Our appreciation goes to the Commonwealth scholarship Commission for an award towards funding this work.

References

1. ICRU: Photon, Electron, Proton and Neutron Interaction Data for Body tissues, International Commission for Radiological Units and Measurements ICRU, Bethesda, USA. 1992.
2. Conway BJ, Duff JE, Fewell TR, Jennings RJ, Rothenberg LN and Fleischman RC. A patient equivalent attenuation phantom for estimating patient exposures from automatic exposure controlled x-ray examinations of the abdomen and lumbo-sacral spine. *Medical Physics* 1990; 17 (3): 448-453.
3. Dell MA. Phantoms for Diagnostic Radiology. *Radiat. Prot. Dosim.* 1990; 49 (1/3): 55-57.
4. Guibelalde E and Vano E. Design criteria for and evaluation of Phantoms employed in conventional radiography. *Radiat. Prot. Dosim*. 1993;49 (1/3): 39-46.
5. Servomaa A and Tapiovaara M. Two new patient equivalent phantoms in diagnostic radiology. *Radiat. Prot. Dosim*. 1992; 43(1-4): 229-231.