Technical Note: Accuracy of MTF measurements with an edge phantom at megavoltage x-ray energies

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Purpose: Measurement of the modulation transfer function (MTF) is performed by evaluating the response of an imaging system to a predefined input. To obtain accurate results when using an edge phantom, the detector input signal must resemble an ideal step function. The MTF of megavoltage (MV) imagers used in radiotherapy has been measured with highly absorbing edge phantoms fabricated from thick metal blocks. This study investigates the influence of the edge phantom design on the accuracy of the resulting MTF.

Methods: The MTF of an electronic portal imaging device (EPID) was measured at 6 MV beam quality with four edge phantoms made of lead with 1.3, 3.3, 5.0, and 10.0 cm thickness. Monte Carlo simulations were carried out for these and a selection of tungsten phantoms to determine the photon fluence at the imaging plane and quantify the systematic error in the MTF introduced by the edge phantom design.

Results: The measured MTF depends on the design of the edge phantom. The detector input signal of a thin phantom is affected by secondary radiation from the phantom itself, causing an overestimation of the MTF. The amount of secondary radiation can be reduced by increasing the phantom thickness or introducing an air gap between the phantom and the detector. Both methods introduce geometric unsharpness, which can result in an underestimation of the true MTF. Edge phantoms made from 4.0 cm thick tungsten or 5.0 cm thick lead induce comparatively small systematic errors of below 3% or 5%, respectively.

Conclusions: When MTF measurements are conducted at MV energies, even a highly absorbing edge phantom will introduce a systematic error of several percent. Direct comparison of MTFs obtained with different edge phantoms should therefore be treated with caution. *© 2019 The Authors. Medical Physics published by Wiley Periodicals LLC on behalf of American Association of Physicists in Medicine.* [https://doi.org/10.1002/mp.13843]

Key words: edge method, megavoltage (MV) x-ray imaging, modulation transfer function (MTF), portal imaging, radiotherapy

1. INTRODUCTION

The spatial resolution of a linear and shift-invariant imaging system can be assessed by measurement of the modulation transfer function (MTF). The MTF is defined as the Fourier amplitude of the system's response to a delta impulse.[1] To measure the MTF of a radiographic system, it is common practice to analyze the image of a sharp edge or a narrow slit. For an accurate MTF measurement result, the detector input signal must be a close approximation of a step function or a delta function.

MTF measurements at MV energies are challenging due to the low absorption of the photon beam and a high level of noise in the image.[2] Previous works have demonstrated MTF measurements with high-absorbing edge or slit phantoms made from thick metal blocks.[3–14] While edge phantoms are easier to align with the radiation beam than slit phantoms, the measurement accuracy can be impaired by scattered radiation from the phantom itself.[13,15]

This work investigates the influence of the edge phantom design on the accuracy of the MTF for MV imaging systems. The MTF of a clinically used MV detector is measured with four lead phantoms. Monte Carlo simulations are performed to determine the detector input signal of these and additional tungsten phantoms. The results are used to calculate the systematic error introduced to the MTF measurement by the edge phantom.

2. MATERIALS AND METHODS

Measurements were performed for a PortalVision aS1200 MV detector (0.336 mm pixel pitch) using the 6MV photon

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beam of a Varian TrueBeam linear accelerator. The source to detector distance (SDD) was set to the maximum of 180 cm. The four edge phantoms consisted of rectangular lead blocks with a sharp edge. The phantoms had a thickness of 1.3, 3.3, 5.0, and 10.0 cm, showing an x-ray transmission of 34%, 10%, 4%, and 0.3%, respectively. Measurement setup and analysis followed the established methods for diagnostic x-ray imaging systems[16,17]: The phantom was placed in direct contact with the front cover of the detector (situated 12 mm in front of the imaging plane) and the edge was aligned with the central axis at an angle of ~2° with respect to the detector array. Images were acquired with an exposure of 40 MU and subjected to gain, offset, and dead pixel correction. Nonuniformities in the ESF (e.g., from backscatter) were investigated using a detrending technique and found to be negligible. The oversampled line spread function (LSF) was calculated from the edge spread function (ESF) by finite element differentiation and symmetrically truncated around the edge transition to a length of 2^{12} data points, corresponding to 5–7 cm (dependent on the edge angle). The MTF was determined as the absolute value of the Fourier transformed LSF and normalized to zero frequency value. It was corrected for the finite element differentiation and adjusted for the actual distances between sampling grid points and edge transition.

The Monte Carlo simulations were carried out with the BEAMnrc code[18] using electron and photon cutoff energies of 0.521 and 0.01 MeV, respectively, and applying range rejection for electrons with energies below 1 MeV.

The scoring plane for the detector input signal was defined at a distance of 180 cm from the radiation source (simplifying the detector to an imaging plane without spatial extension). The rectangular scoring field was centered around the edge transition and divided into 400 bins of 0.2 mm width.

The edge phantom was modeled as a rectangular slab and positioned either in direct contact with the scoring plane (as illustrated in Fig. 1) or separated by a small air gap.

We implemented the output of a 6 MV photon beam using TrueBeam Monte Carlo Data Package.[19] The number of particle histories was increased to a total of 10^{10} by running each simulation four times with the TrueBeam phase space being rotated by 90° around the central axis and averaging the results.

To obtain a more finely sampled detector input signal, we used an oversampling technique similar to the use of an angled phantom during MTF measurement. The photon fluence was scored 26 times, while the scoring field was moved by increments of 1/26 of the bin width with respect to the edge transition. The 26 data sets were interlaced to produce a detector input signal with a sample spacing of 0.2 mm/ 26 = 0.0077 mm.

MTF analysis of the simulated edge images was conducted as described above. In addition, the MTF was divided by $|sinc(\pi \cdot 0.2\text{mm} \cdot \xi)|$ to correct for the scoring bin width of 0.2 mm. The resulting MTF describes the systematic error introduced to the MTF measurement by the difference between the detector input signal and an ideal step function. We call this the phantom MTF. An ideal step function will produce a phantom MTF which is unity at all spatial frequencies.

3. RESULTS

Figure 2 shows distinct differences in the MTF measurement results of the PortalVision aS1200 detector. MTF_{50} was determined at 0.49, 0.39, 0.35, and 0.27 mm^{-1}, demonstrating an overall decrease of the measured MTF with increased phantom thickness. The manufacturer-specified value of MTF_{50} = 0.35 mm^{-1} (measured with a slit phantom) matches the result of the 5 cm lead phantom.

As the MTF cannot take values greater than unity per definition, the peak at around 0.05 mm^{-1} in the MTF measured with the 1.3 cm lead phantom strongly indicates that the underlying detector input signal did not resemble a step function.

The simulated photon fluence in Fig. 3(a) illustrates that this phantom creates a high amount of secondary radiation, which leads to distortions around the edge transition. With increased phantom thickness, secondary radiation is absorbed

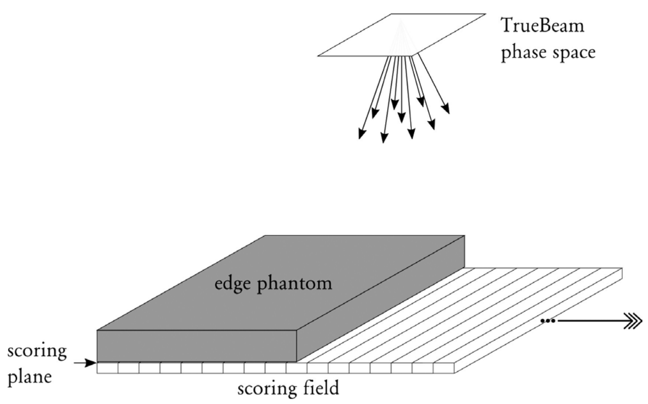

FIG. 1. Geometry used for Monte Carlo simulations of the detector input signal.

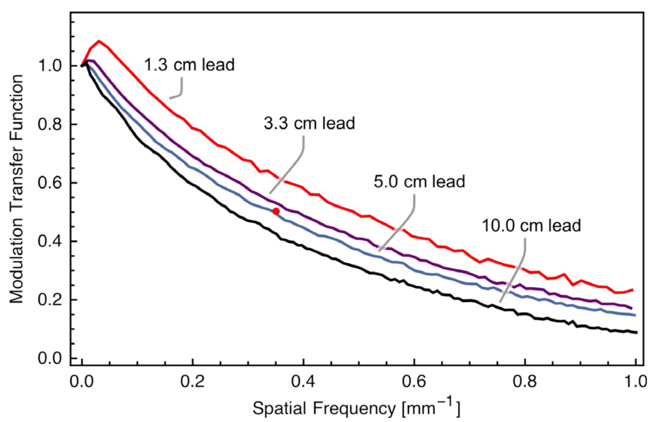

FIG. 2. MTF of the PortalVision aS1200 detector acquired with edge phantoms made of lead with a thickness of 1.3 cm (red), 3.3 cm (purple), 5.0 cm (blue), and 10.0 cm (black). Red dot marks the MTF_{50} = 0.35 mm^{-1} specified by the manufacturer. [Color figure can be viewed at wileyonlinelibrary.com]

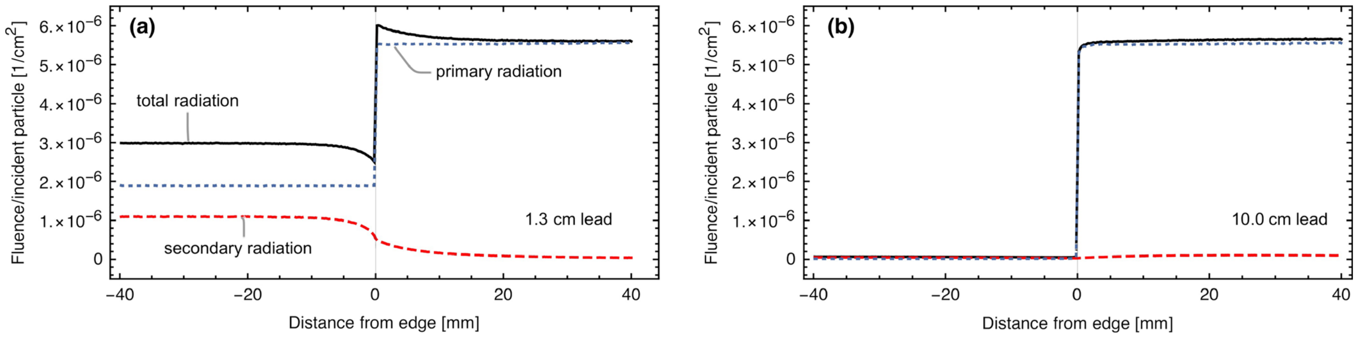

FIG. 3. Detector input signal produced by edge phantoms made of lead with a thickness of (a) 1.3 cm and (b) 10.0 cm. Total photon fluence (black), fluence from primary radiation (blue), and fluence from secondary radiation (red) were obtained by Monte Carlo simulation. [Color figure can be viewed at wileyonlinelibrary.com]

by the phantom itself and does not reach the detector plane. On the other hand, the entrance plane of a thick phantom is situated at a greater distance from the detector plane, causing a slope of the primary radiation due to geometric unsharpness [Fig. 3(b)].

The phantom MTFs shown in Fig. 4 were calculated from the simulated photon fluences and indicate the achievable accuracy of the MTF measurement with the respective edge phantom design. For thin phantoms, the influence of secondary radiation leads to an overestimation of the MTF, which is approximately constant with spatial frequency. This result agrees with previous findings by Neitzel et al.[15] for partially absorbing edge phantoms at kV radiation qualities. When the thickness of the phantom is increased, the impact of secondary radiation is reduced. At the same time, the influence of geometric unsharpness becomes apparent in the steady decrease of the phantom MTF with spatial frequency. Of the four edge phantoms used for measurement, the phantom made from 5.0 cm thick lead produces the most accurate MTF result. This confirms the good agreement with the specified MTF_{50} seen in Fig. 2. In the spatial frequency range up to 1 mm^{-1}, this phantom design introduces a maximum error of <5 %.

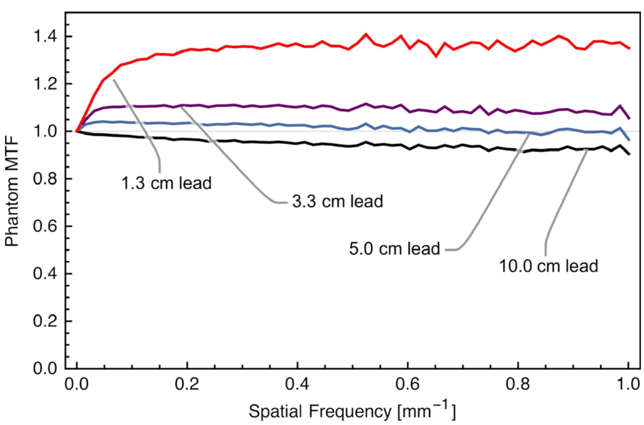

FIG. 4. Phantom modulation transfer function indicating the systematic measurement error introduced by an edge phantom made of 1.3 cm (red), 3.3 cm (purple), 5.0 cm (blue), and 10.0 cm (black) thick lead. [Color figure can be viewed at wileyonlinelibrary.com]

Additional simulations showed that an even higher accuracy can be obtained with a tungsten edge phantom of 4.0 cm thickness, which introduces a maximum error of 3% to the MTF measurement. Table I lists all simulated edge phantoms and the values of the corresponding phantom MTFs at selected spatial frequencies.

Figure 5 illustrates the effects of an alternative scatter reduction proposed by Star-Lack et al.[13] Instead of increasing the phantom thickness, a small air gap between phantom and detector is introduced. By elevating the phantom, the scatter distribution in the central area around the edge transition is stretched and thereby homogenized.

With increasing air gap distance, the contribution from scatter resembles a constant offset and the measurement accuracy is improved (Fig. 6). On the other hand, the geometric unsharpness introduced by the air gap causes the measured MTF to decrease with spatial frequency.

TABLE I. Phantom modulation transfer function (MTF) at selected spatial frequencies derived from Monte Carlo simulations for several edge phantom designs, assuming 6 MV beam quality and 180 cm SDD. The MTF values indicate the systematic measurement error introduced by the phantom.

Phantom	Phantom MTF ($0.1\ mm^{-1}$)	Phantom MTF ($0.5\ mm^{-1}$)	Phantom MTF ($1.0\ mm^{-1}$)
Lead, 1.3 cm	1.29	1.35	1.35
Lead, 3.3 cm	1.11	1.09	1.06
Lead, 5.0 cm	1.04	1.01	0.97
Lead, 10.0 cm	0.98	0.94	0.91
Tungsten, 1.0 cm	1.28	1.36	1.34
Tungsten, 1.0 cm, with 5 cm air gap	1.22	1.16	1.12
Tungsten, 1.0 cm, with 10 cm air gap	1.11	1.00	0.96
Tungsten, 1.0 cm, with 20 cm air gap	1.01	0.90	0.80
Tungsten, 3.0 cm	1.06	1.05	1.02
Tungsten, 4.0 cm	1.02	1.00	0.97
Tungsten, 5.0 cm	1.00	0.97	0.93
Tungsten, 10.0 cm	0.98	0.94	0.90
Tungsten, 20.0 cm	0.97	0.93	0.88

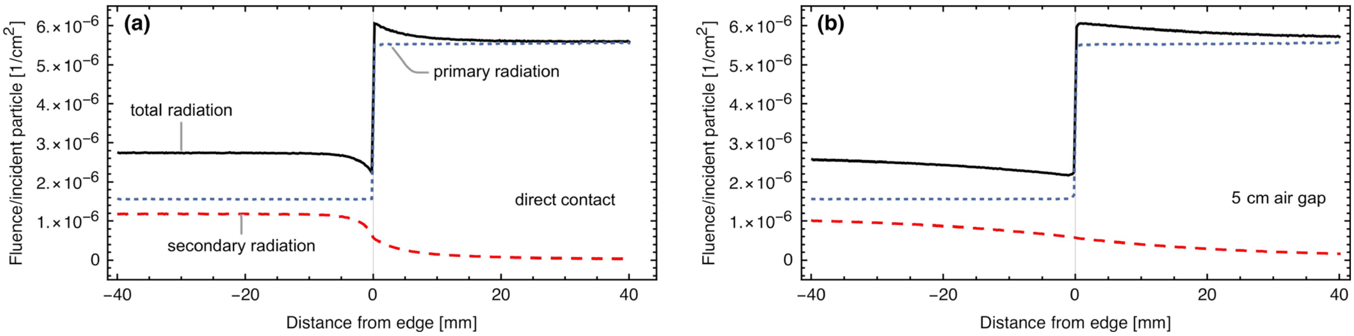

FIG. 5. Detector input signal produced by a 1.0 cm thick tungsten edge phantom, positioned (a) in direct contact with the detector and (b) with an air gap of 5 cm. Total photon fluence (black), fluence from primary radiation (blue), and fluence from secondary radiation (red) were obtained by Monte Carlo simulation. [Color figure can be viewed at wileyonlinelibrary.com]

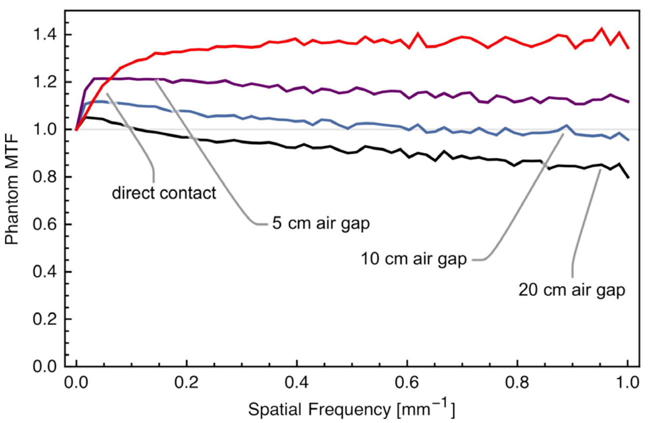

FIG. 6. Phantom modulation transfer function indicating the systematic error introduced by an edge phantom of 1.0 cm tungsten, in direct contact (red) with the detector or separated by an air gap of 5.0 cm (purple), 10.0 cm (blue) and 20.0 cm (black). [Color figure can be viewed at wileyonlinelibrary.com]

4. DISCUSSION

The results of our study show that the measured MTF strongly depends on the design of the edge phantom. Insufficient absorption of incident MV photons causes the photon fluence behind the phantom to deviate from the ideal step-function shape. Consequently, the measured MTF is not the true MTF.

Both secondary radiation and geometric unsharpness compromise the accuracy of the MTF measurement, though with opposite consequences. Secondary radiation leads to an overestimation which is constant over the entire spatial frequency range and can be recognized by MTF values greater than unity at low spatial frequencies. Geometric unsharpness results in an underestimation of the MTF which becomes more pronounced with increasing spatial frequency. While increasing the phantom thickness, the amount of secondary radiation reduces, it simultaneously introduces geometric unsharpness. Due to the trade-off between these effects, the phantom with the highest x-ray absorption does not necessarily provide the most accurate measurement result.

Our simulations show that the use of a 4.0 cm thick tungsten phantom achieves a compromise with MTF values within 3 % of the true values in the spatial frequency range up to 1 mm^{-1}. By comparison, the accuracy which can be achieved for MTF measurements at kV radiation qualities is in the order of 0.1%.[15] Significant further improvement of the accuracy with a different edge phantom design seems unlikely, as it would require a higher beam attenuation without an increase in the phantom thickness. This implies that measurements at a higher beam energy than 6 MV will likely be even more challenging due to the overall lower x-ray absorption.

Elevating the phantom from the detector is an effective measure to reduce the impact of secondary radiation generated by thin phantoms. However, the simultaneously introduced geometric unsharpness can also impair the measurement accuracy. While we have found this measurement setup to be unsuitable for a clinical linear accelerator with a maximum SDD of 180 cm, it may be of interest if a greater SDD can be realized.

The Monte Carlo simulations modeled the particle transport up to the imaging plane, but did not include the detector. The results are therefore applicable to all MV imaging devices used with a comparable beam quality, including EPIDs as well as two-dimensional ion chamber arrays.

Additional studies should investigate the systematic errors introduced by measurement with a slit phantom and compare them to the findings of this study.

5. CONCLUSIONS

Accurate measurement of the MTF for detectors used at megavoltage x-ray energies is a challenging task. Depending on the design of the phantom, the detector input signal will be influenced by secondary radiation or geometric unsharpness, which causes an over- or underestimation of the true MTF, respectively. Comparisons of MTFs obtained with different edge phantoms should be treated with caution.

In the spatial frequency range up to 1 mm^{-1}, the MTF can be measured within 3% accuracy using a tungsten edge phantom with 4.0 cm thickness. Alternatively, an edge phantom made from 5.0 cm thick lead will return the MTF with an accuracy of 5%.

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CONFLICT OF INTEREST

The authors have no conflict to disclose.

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