A design Framework of Edge Phantoms for Accurate MTF Measurement at Megavoltage X-Ray Energies

Seungha Son[1], Jinwoo Kim[2], Seungjun Yoo[1], and Ho Kyung Kim[1,2*]

[1]School of Mechanical Engineering, Pusan National University, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 46241, Republic of Korea
[2]Center for Advanced Medical Engineering Research, Pusan National University, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 46241, Republic of Korea
*Correspondence: hokyung@pusan.ac.kr

Introduction

Motivation

- Cargo-container screening at port generally utilizes an x-ray beam with megavoltage (MV) energies (while kilovoltage (kV) energies are predominantly used in diagnostic radiology)
- The MV image quality can be evaluated as same as done in the conventional kV images, and which consists mainly of the contrast, the noise, and the spatial resolution
- The modulation-transfer function (MTF) is known as the most objective and quantitative metric for the assessment of system spatial resolving power

Objectives

- To develop a design framework of the edge-spread function (ESF) at MV energies using the Monte Carlo (MC) technique
- To find materials and to determine its thickness producing secondary radiations as low as possible

Materials and Methods

Ideal ESF and MTF

- For an ideal impulse signal $\delta(x,y)$, the LSF $l(x)$ is given by

$$l(x) = \int_{-\infty}^{\infty} \delta(x,y)\,dy = \delta(x)$$

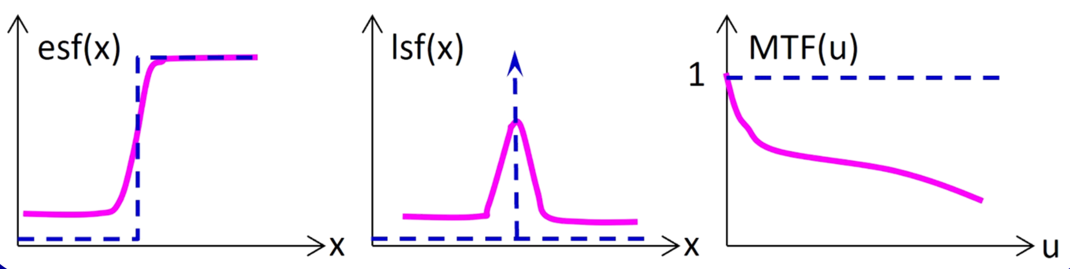
- The corresponding MTF is evaluated as

$$\mathrm{MTF}(u) = \left|\mathcal{F}\left\{\frac{l(x)}{\int_{-\infty}^{\infty} l(x)\,dx}\right\}\right| = \frac{|T(u)|}{|T(0)|} = 1$$

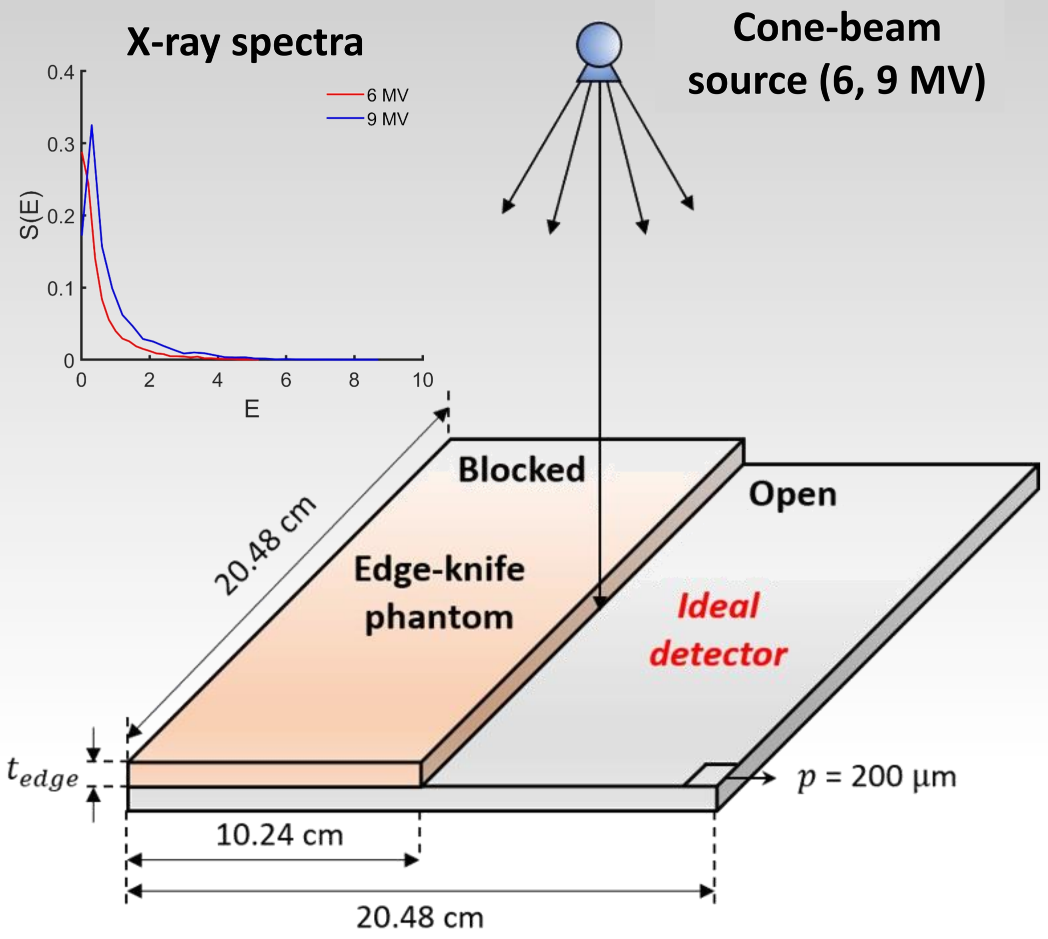
- While the LSF can be directly obtained from the slit phantom, the finite extent of slit gap derives $\delta(x)$ to be blurred
- Instead, since the relationship between ESF $e(x)$ and LSF $l(x)$ is established as

$$l(x) = \frac{de(x)}{dx}$$

- The MTF can be readily estimated from the ESF measurement. However, the error or noise during numerical differentiation is a drawback



Monte Carlo framework

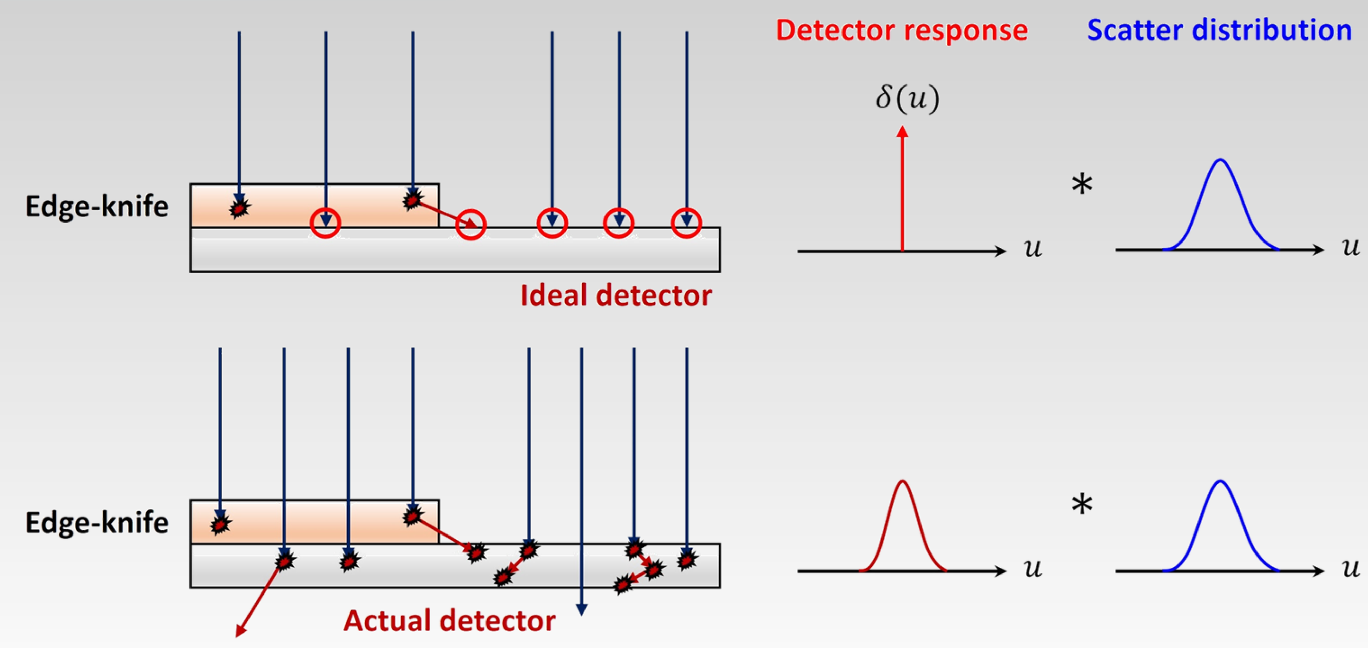


Parameter	Value
Peak voltage (MV)	6, 9
Edge material	W, Pb, Cu, Fe
Transmittance τ (%)	0.01, 0.1, 0.5, 1, 5
t_{edge} (cm)	Corresponding to τ
Pixel pitch (mm)	0.2
# of pixels	1024 × 1024

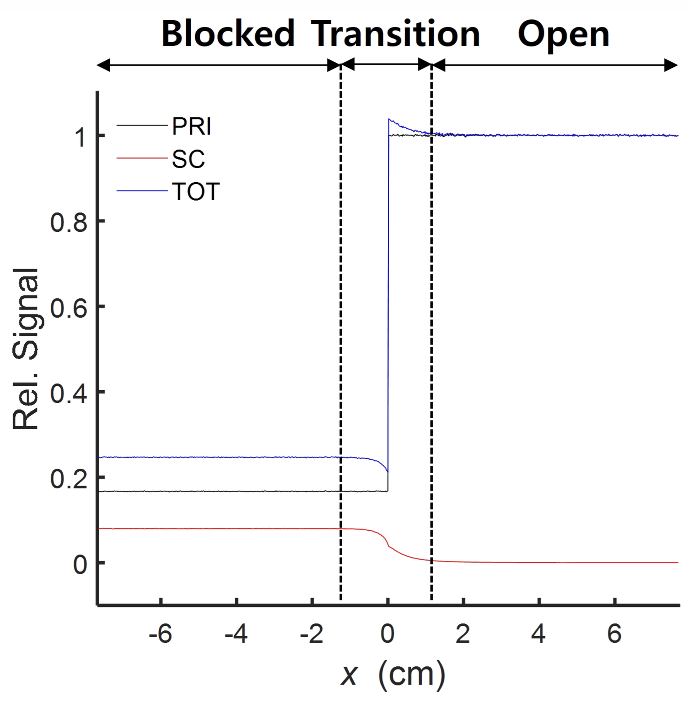
Transmittance

$$\tau = \frac{\int_{-\infty}^{\infty} S_0(E)e^{-\mu(E)t_{edge}}\,dE}{\int_{-\infty}^{\infty} S_0(E)\,dE} \times 100\ (\%)$$

Ideal detector model



ESF analysis



Metric	Equation
Scatter-to-primary ratio	$\bar{\varepsilon}_{SC}^{BL}/\bar{\varepsilon}_{PRI}^{BL}$
Scatter fraction	$\bar{\varepsilon}_{SC}^{BL}/\bar{\varepsilon}_{TOT}^{BL}$
Undershoot	$\frac{\bar{\varepsilon}_{TOT}^{BL} - \min(\varepsilon_{TOT})}{\bar{\varepsilon}_{TOT}^{BL}}$
Overshoot	$\frac{\max(\varepsilon_{TOT}) - \bar{\varepsilon}_{TOT}^{OP}}{\bar{\varepsilon}_{TOT}^{OP}}$
Offset level	$\frac{\bar{\varepsilon}_{TOT}^{BL} - \bar{\varepsilon}_{PRI}^{BL}}{\bar{\varepsilon}_{PRI}^{BL}}$

ε = measured energy

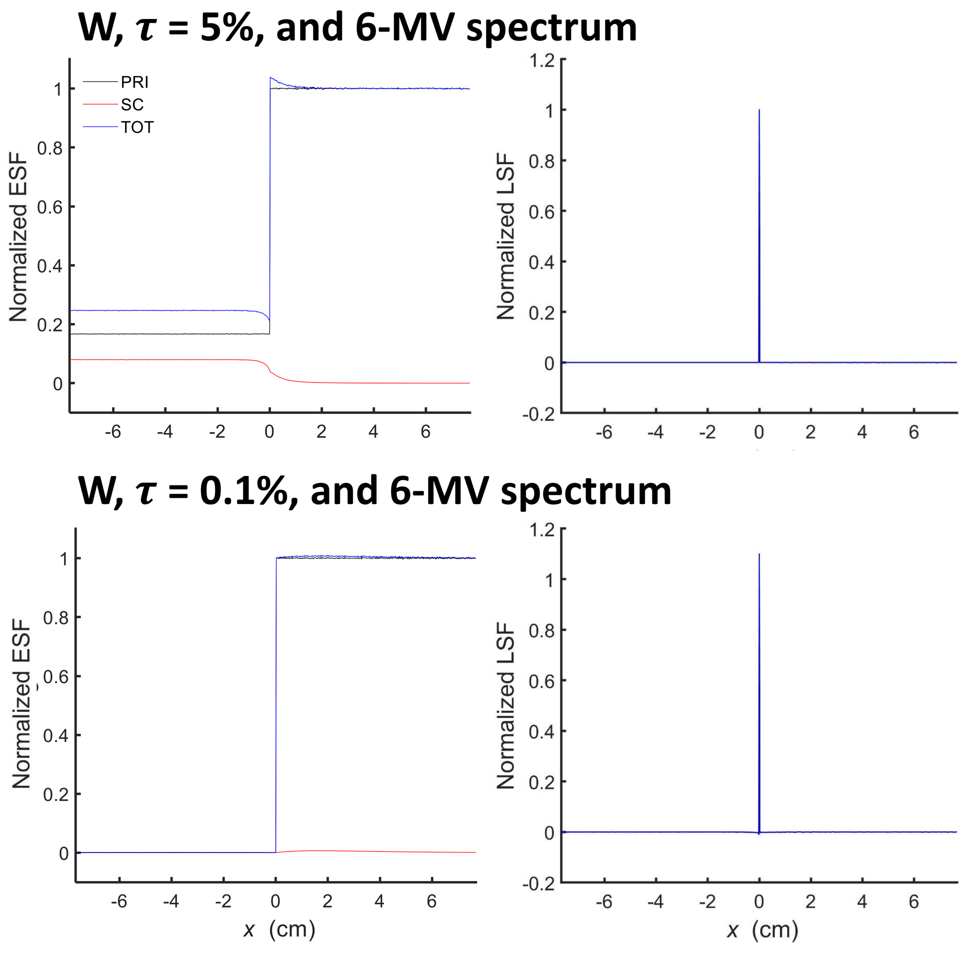
- To reduce the fluctuation in the MTF, the ESFs were regressed using the Gaussian-weighted moving average method

Results

ESF & LSF analyses

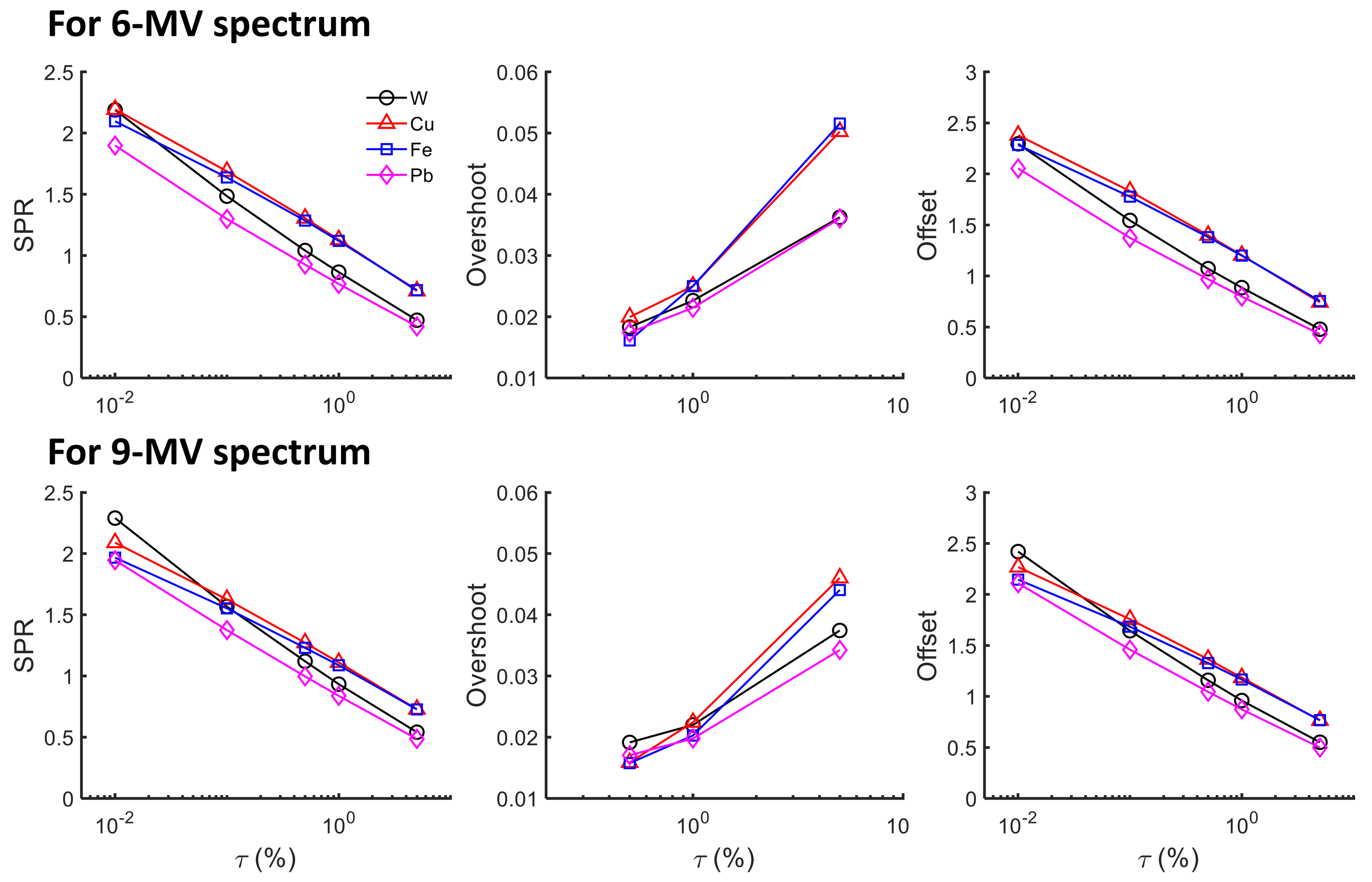
W, τ = 5%, and 6-MV spectrum

W, τ = 0.1%, and 6-MV spectrum



For 6-MV spectrum

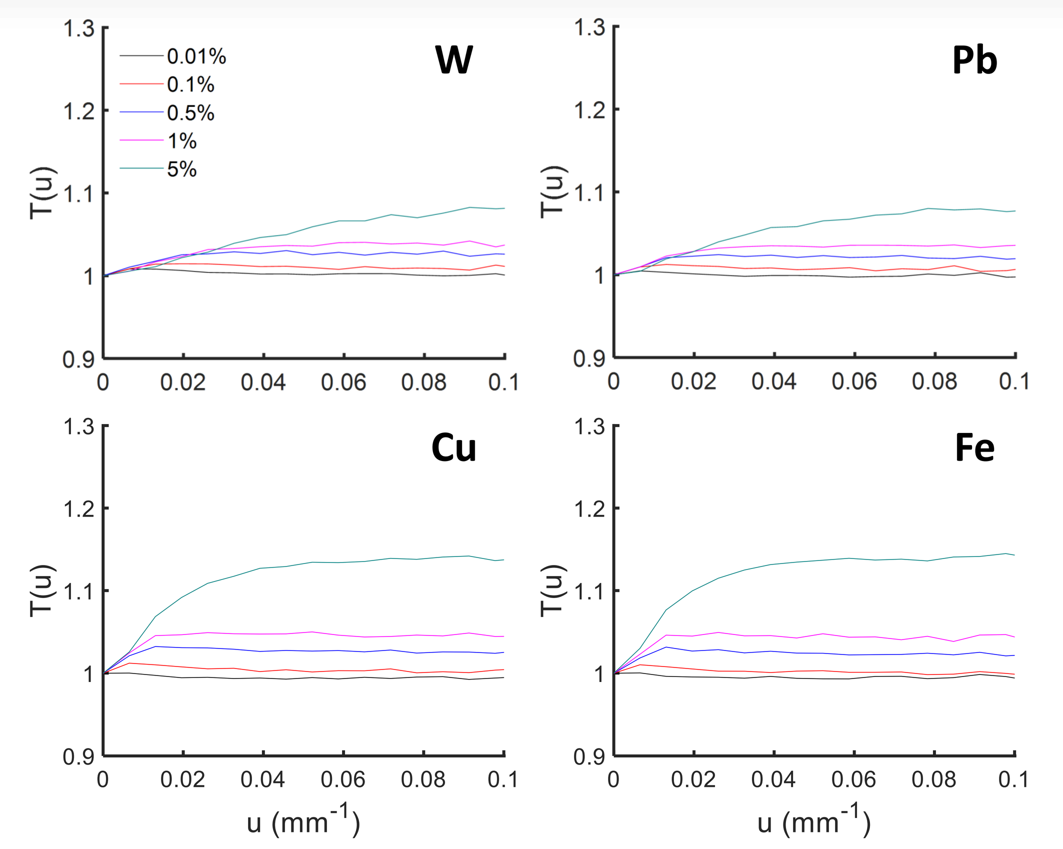
For 9-MV spectrum



- The SPR, SF, and offset level measured in the blocked area were exponentially increased with the t_{edge}
- Overshoot and undershoot in transition area were effectively suppressed as the t_{edge} increases

MTF analysis

Resultant MTFs for 6-MV spectrum



- For each material, $\tau \le 0.1\%$ shows nearly ideal responses, while large distortion is observed for higher τ values
- The Cu and Fe show larger distortion of MTF due to higher probable Compton interactions

Discussion and Conclusion

- The impulse responses of the *ideal* flat-panel detector for MV x-ray spectra were widely investigated for various designs of the edge-knife phantom
- To correctly evaluate the MV MTFs by edge-knife measurement, τ should be at least less than 0.1% since the overshoot and undershoot may significantly contaminate the $l(x) = \frac{de(x)}{dx}$ (they can cause the *negative* $l(x)$)
- For $\tau > 0.1\%$, the materials with low-probable Compton interactions (i.e., with low μ_{CS}/μ; thus W, Pb rather than Cu, Fe) can provide less artifact (=overestimation) in MTF
- Our next work will be the experimental validation of ESF analysis and the consideration of the line-scanning motion, which is typical for the MV cargo container screening systems

Radiation Imaging Laboratory {http://ril.pusan.ac.kr}

This work was conducted as a part of the research projects of "Development of automatic screening and hybrid detection system for hazardous material detecting in port container" financially (20200611) supported by the Ministry of Oceans and Fisheries, Korea.