Dual-energy imaging performance in sandwich detectors for mouse imaging

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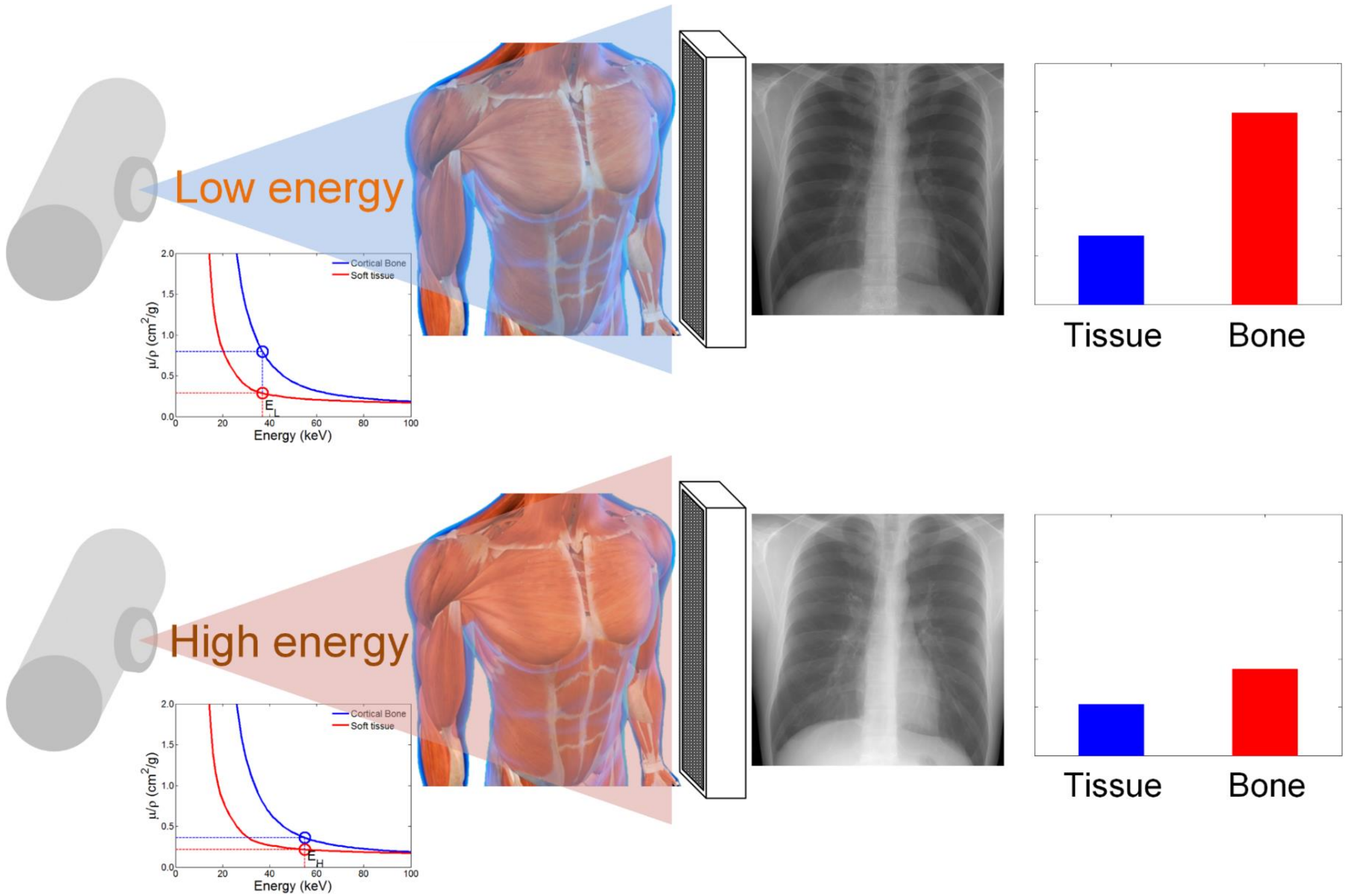
Dual-energy imaging



R. E. Alvarez et al., *Med. Phys.* (2004)

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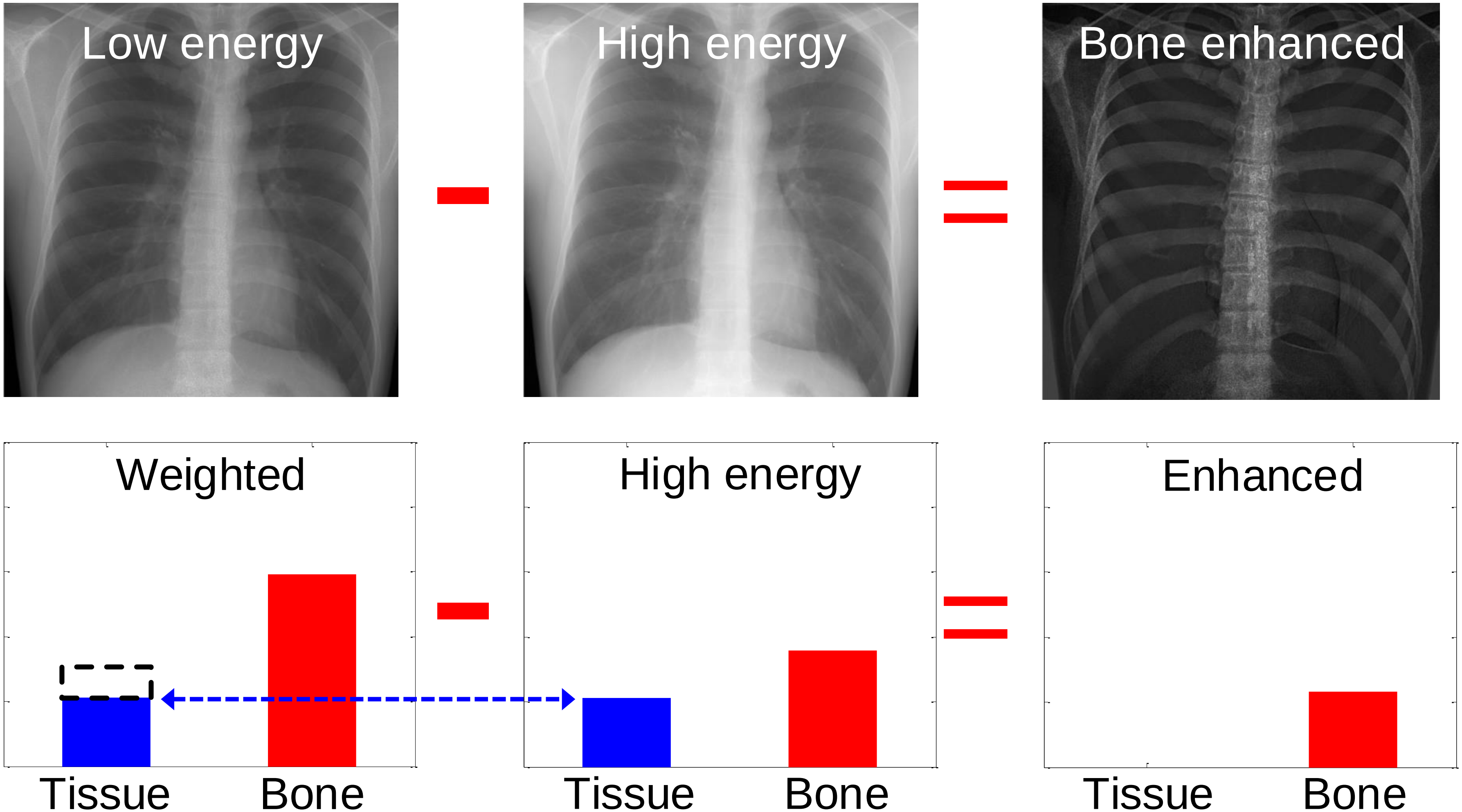
Dual-energy imaging



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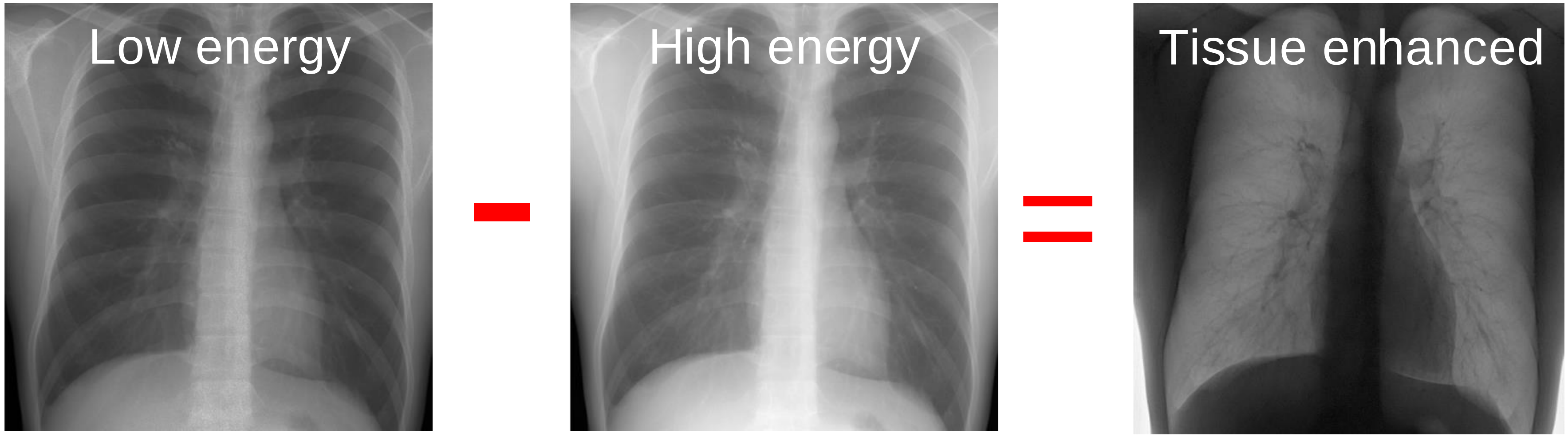
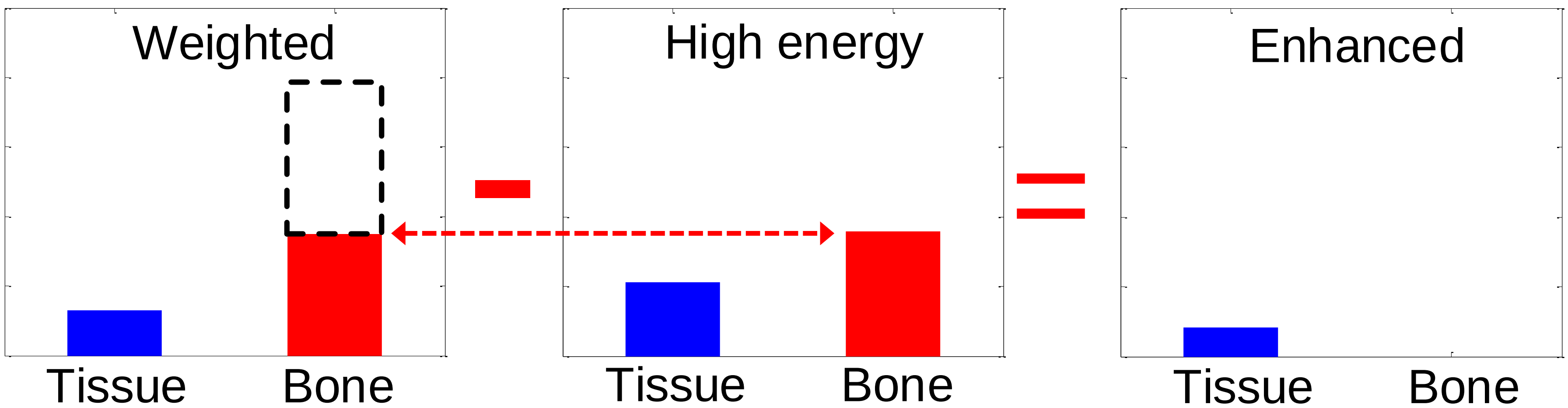
Dual-energy imaging





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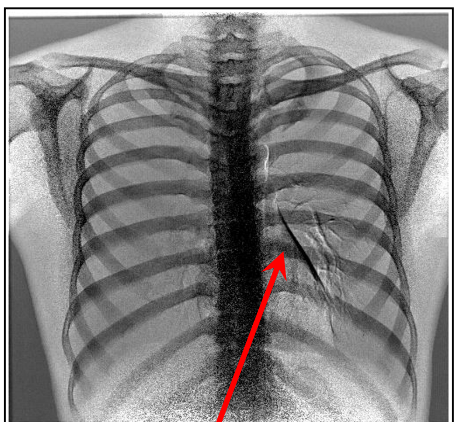
Motivation

- Dual-energy imaging is vulnerable to motion artifacts during registration of two successive images
- The sandwich detector can avoid motion artifacts by acquiring the high and low images at the same time



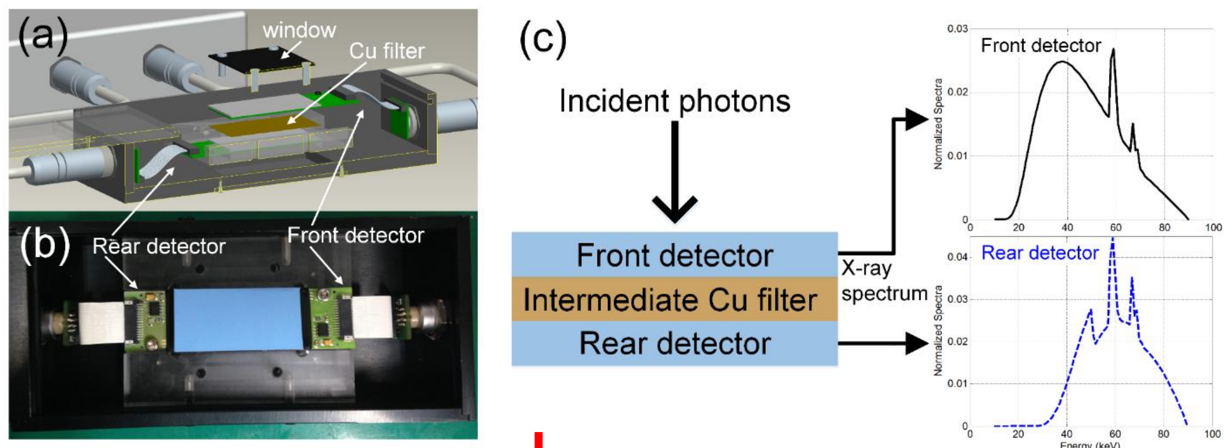
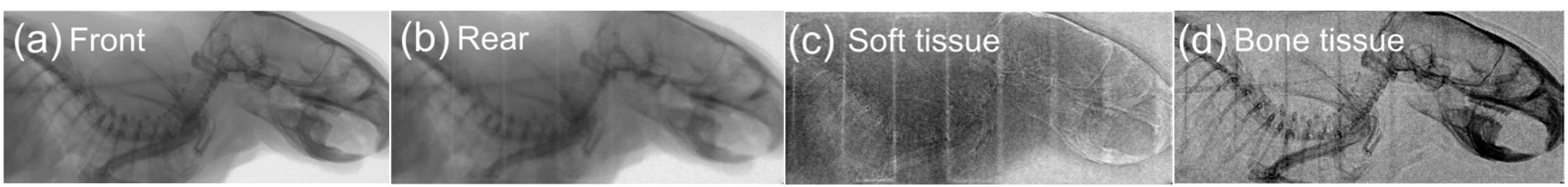


Image quality – kVp, t_{IF}



J. C. Han et al., *Curr. Appl. Phys.* (2014)

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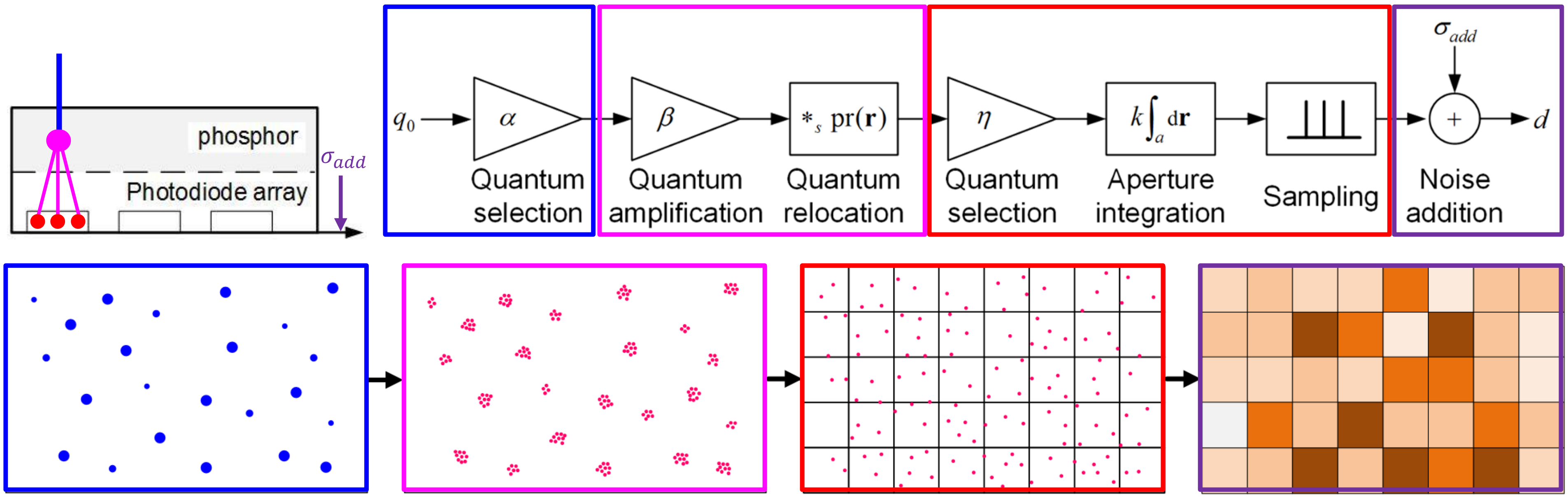
Modeling

- A simple cascaded-systems model describing the signal and noise propagation in an indirect flat-panel detector



$$\bar{d}_j = ka^2\bar{q}\bar{\tau}_j\bar{g}_j$$

$$W'_{j,indirect}(u) = \frac{\bar{m}^2_{j,indirect}}{\bar{q}_0\tau_j\bar{g}^2_j}\left[\frac{1}{\gamma\bar{m}_{j,indirect}} + \frac{1}{\bar{\alpha}_j}\left(\frac{1}{I_{F,indirect}} - \frac{1}{\bar{\beta}_j}\right)T^2_{j,alias}(u)\right]$$

$$W'_{j,direct}(u) = \frac{\hat{\alpha}_j\bar{m}^2_{j,direct}}{\gamma\bar{q}_0\bar{\xi}_j\tau_j I_{j,direct}\bar{g}^2_j}, \qquad W'_{j,add}(u) = \frac{\sigma^2_{j,add}}{\gamma a^2\bar{q}^2_0\tau^2_j\bar{g}^2_j}$$

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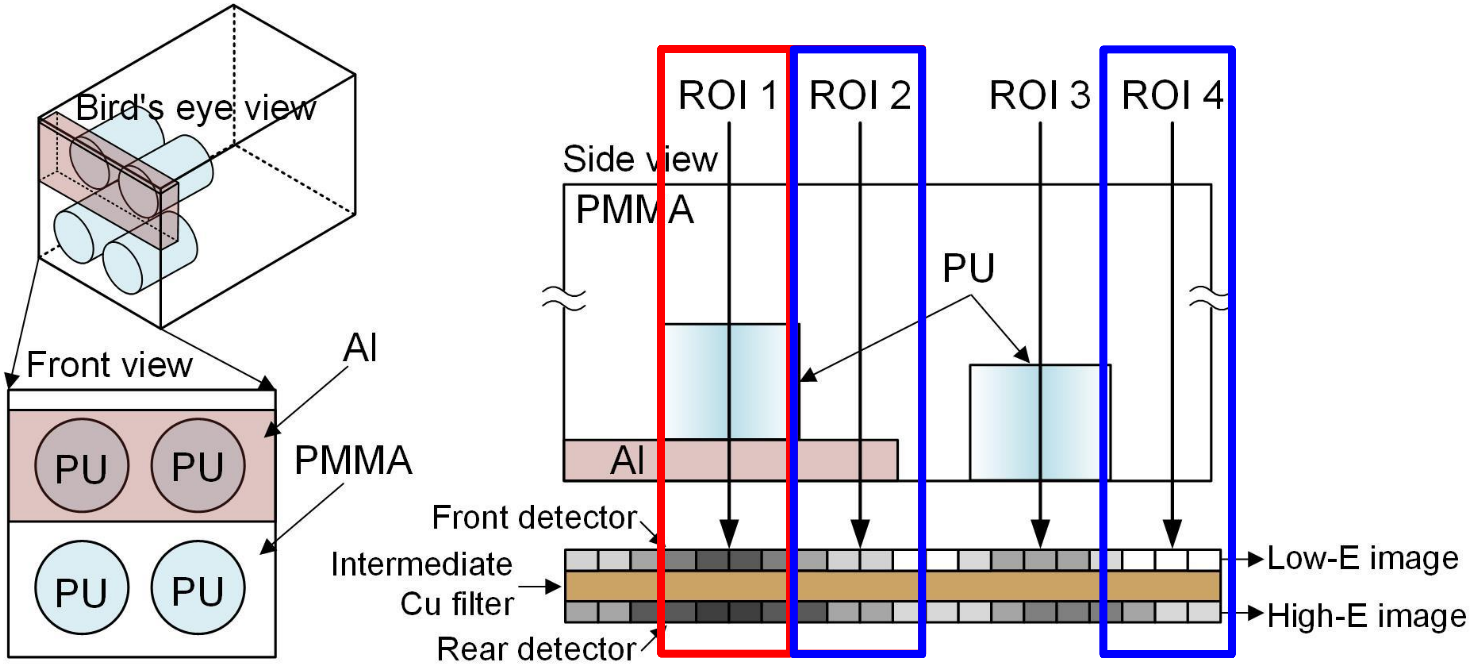
DE contrast model

- The contrast in DE images may be expressed in attenuation coefficienct:



$$p^{DE} = p^H - w \times p^L = \ln\left(\frac{I^H}{I_0^H}\right) - w \times \ln\left(\frac{I^L}{I_0^L}\right) = \mu_{\mathrm{M}}^H(t_{\mathrm{M}} - t_j) + \mu_j^H t_j - w\left[\mu_{\mathrm{M}}^L(t_{\mathrm{M}} - t_j) + \mu_j^L t_j\right]$$

- Al-enhanced $C_{24} = \left|p_2^{DE} - p_4^{DE}\right| = \left|\left(w\Delta\mu_{\mathrm{AlPMMA}}^L - \Delta\mu_{\mathrm{AlPMMA}}^H\right)t_{\mathrm{Al}}\right|$
- PU-enhanced $C_{12} = \left|p_1^{DE} - p_2^{DE}\right| = \left|\left(w\Delta\mu_{\mathrm{PUPMMA}}^L - \Delta\mu_{\mathrm{PUPMMA}}^H\right)t_{\mathrm{PU}}\right|$

$$\Delta\mu_{jM}^i = \mu_j^i - \mu_M^i$$

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DE noise model

S. Richard and J. H. Siewerdsen, *Med. Phys.* (2007)

- The noise in DE images may be expressed in the zero-frequency DQE form:

$$p^{DE} = p^H - w \times p^L = \ln\left(\frac{I^H}{I_0^H}\right) - w \times \ln\left(\frac{I^L}{I_0^L}\right)$$

Error propagation

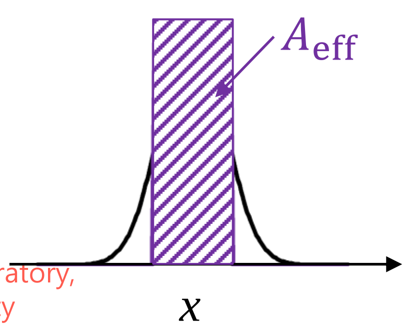
$$\sigma_j^2 = w_j^2 \left(\frac{\sigma^F}{I^F}\right)^2 + \left(\frac{\sigma^R}{I^R}\right)^2$$

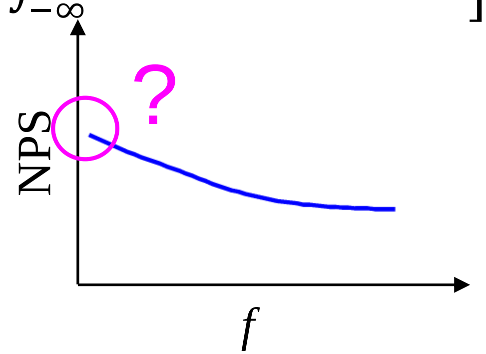
$$= \frac{w_j^2}{(\mathrm{SNR}^F)^2} + \frac{1}{(\mathrm{SNR}^R)^2} = \frac{w_j^2}{\mathrm{DQE}^F(0)\bar{q}_0 X A_{\mathrm{eff}}^F} + \frac{1}{\mathrm{DQE}^R(0)\bar{q}_0 X A_{\mathrm{eff}}^R}$$

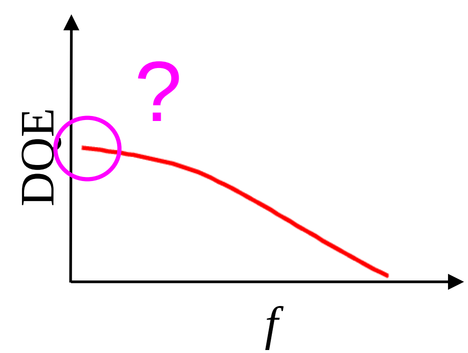
$$\mathrm{SNR} = \frac{\bar{d}^2}{\sigma_d^2} = \mathrm{DQE}(0)\bar{q}A_{\mathrm{eff}}$$

$$\mathrm{DQE}(0) = \frac{1}{\bar{q}\left[\mathrm{NPS}(0)/\bar{d}^2\right]} = \frac{\bar{d}^2}{\bar{q}A_{\mathrm{eff}}\sigma_d^2}$$

$$\mathrm{NPS}(0) = \left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{MTF}_{\mathrm{pre}}^2(u,v)\,\mathrm{d}u\mathrm{d}v\right]^{-1}\sigma_d^2 = A_{\mathrm{eff}}\sigma_d^2$$

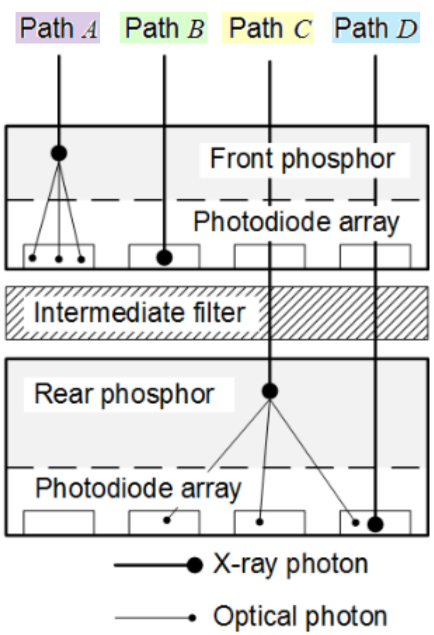


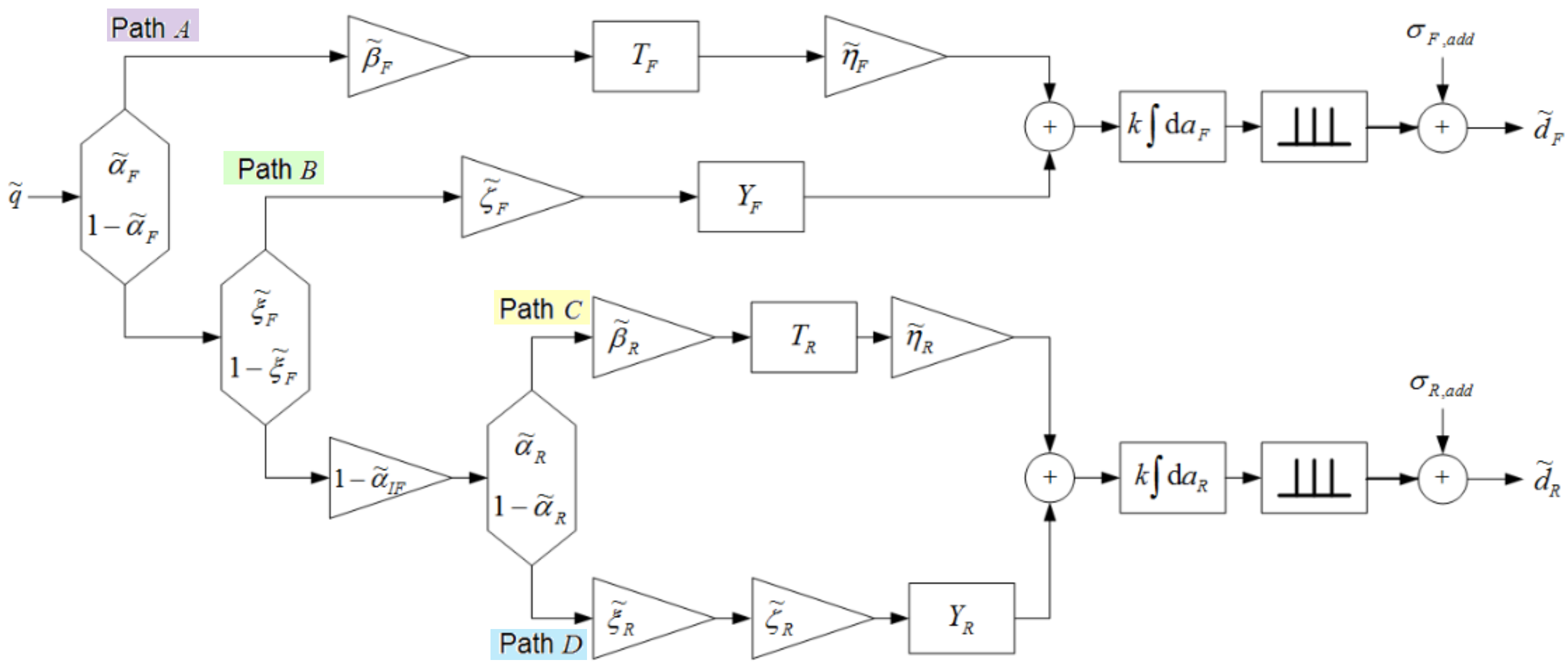




Modeling

- A cascaded-systems model describing the signal and noise propagation in sandwich detector
- A model including the direct interaction of x-ray photons with the photodiode layer that is unattenuated by the phosphor





D. W. Kim et al., *J. Instrum.* (2016)

FOM model

- The FOM in DE images using contrast model and noise model:

$$C_{j\mathrm{M}} = \left|\left(w\Delta\mu_{jM}^{L} - \Delta\mu_{j\mathrm{M}}^{H}\right)t_j\right|$$

$$\sigma_{obj}^{2} = Kf^{-b}\mathrm{MTF}^2(f)$$

$$\mathrm{FOM}_j = \frac{\mathrm{CNR}_j^2}{X} = C_j^2\left[X\left\{w_j^2\left(\left(\sigma_{\mathrm{det}}^{F}\right)^2 + \left(\sigma_{\mathrm{obj}}^{F}\right)^2\right) + \left(\sigma_{\mathrm{det}}^{R}\right)^2 + \left(\sigma_{\mathrm{obj}}^{R}\right)^2\right\}\right]^{-1}$$

$$\sigma_j^2 = w_j^2\left(\frac{\sigma^F}{I^F}\right)^2 + \left(\frac{\sigma^R}{I^R}\right)^2$$

$$= \frac{w_j^2}{(\mathrm{SNR}^F)^2} + \frac{1}{(\mathrm{SNR}^R)^2} = \frac{w_j^2}{\mathrm{DQE}^F(0)\bar{q}_0 X A_{\mathrm{eff}}^{F}} + \frac{1}{\mathrm{DQE}^R(0)\bar{q}_0 X A_{\mathrm{eff}}^{R}}$$

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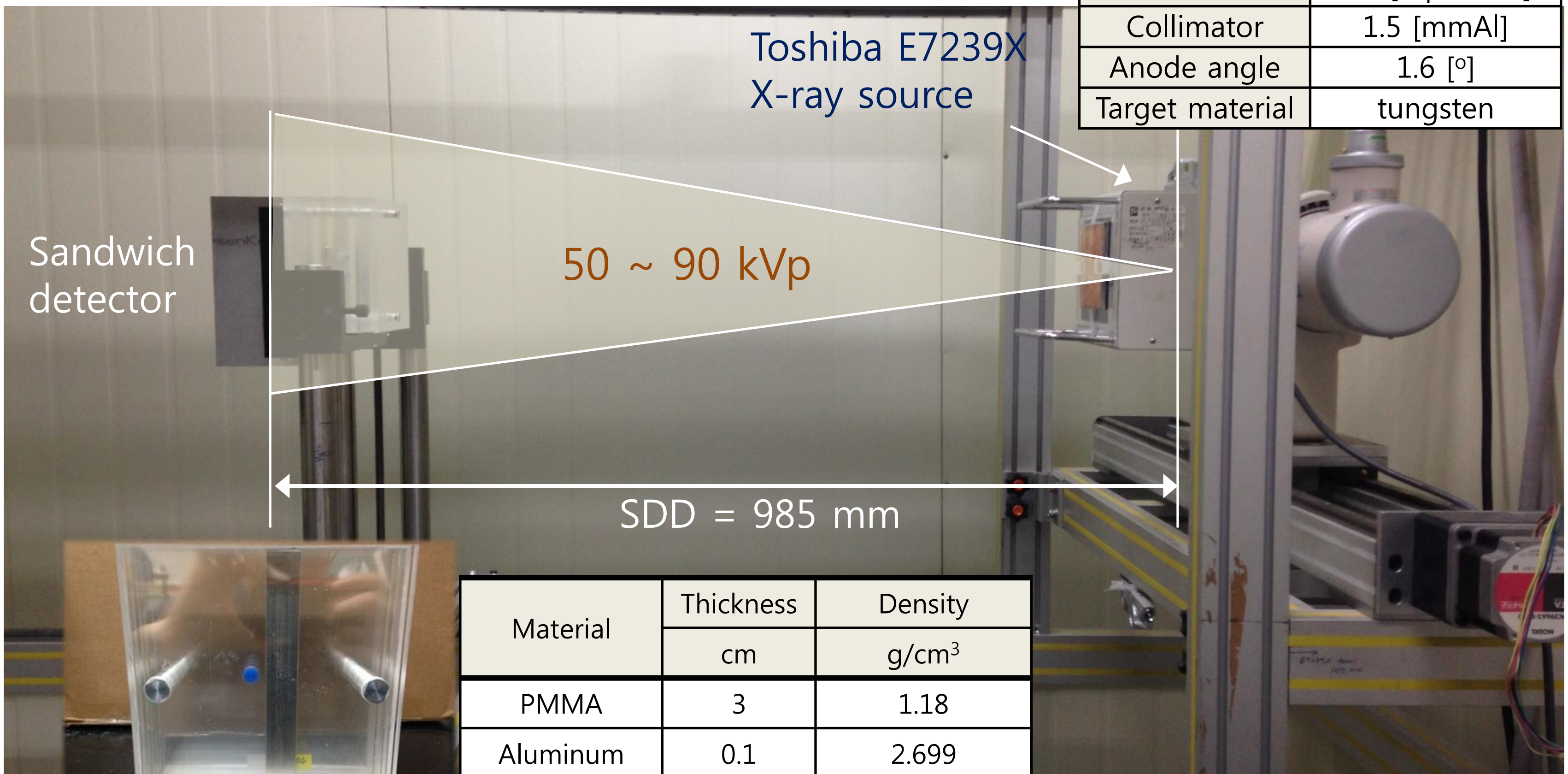
Experimental setup

X-ray Tube	Toshiba E7239X
Inherent filter	0.9 [eq-mmAl]
Collimator	1.5 [mmAl]
Anode angle	1.6 [º]
Target material	tungsten



Designed Phantom

Material	Thickness	Density
	cm	g/cm^3
PMMA	3	1.18
Aluminum	0.1	2.699
Polyurethane	0.3	1.18(PD 50 %)

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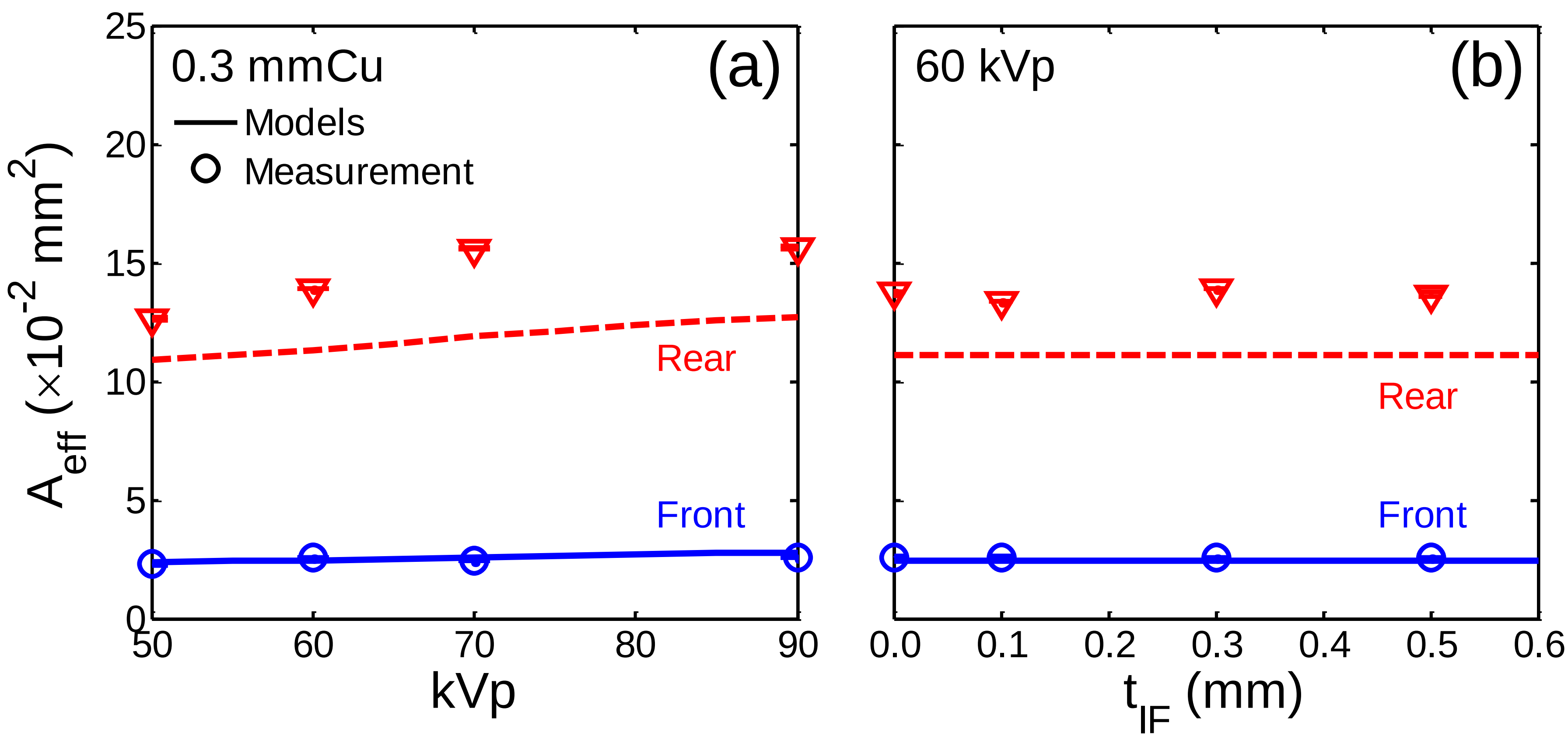
Effective aperture

- Validation between measured in sandwich detector and CSA model
- $A_{\mathrm{eff}} = \left[2\pi \int_0^\infty \mathrm{MTF}_{\mathrm{pre}}^2(f) f \mathrm{d}f\right]^{-1}$



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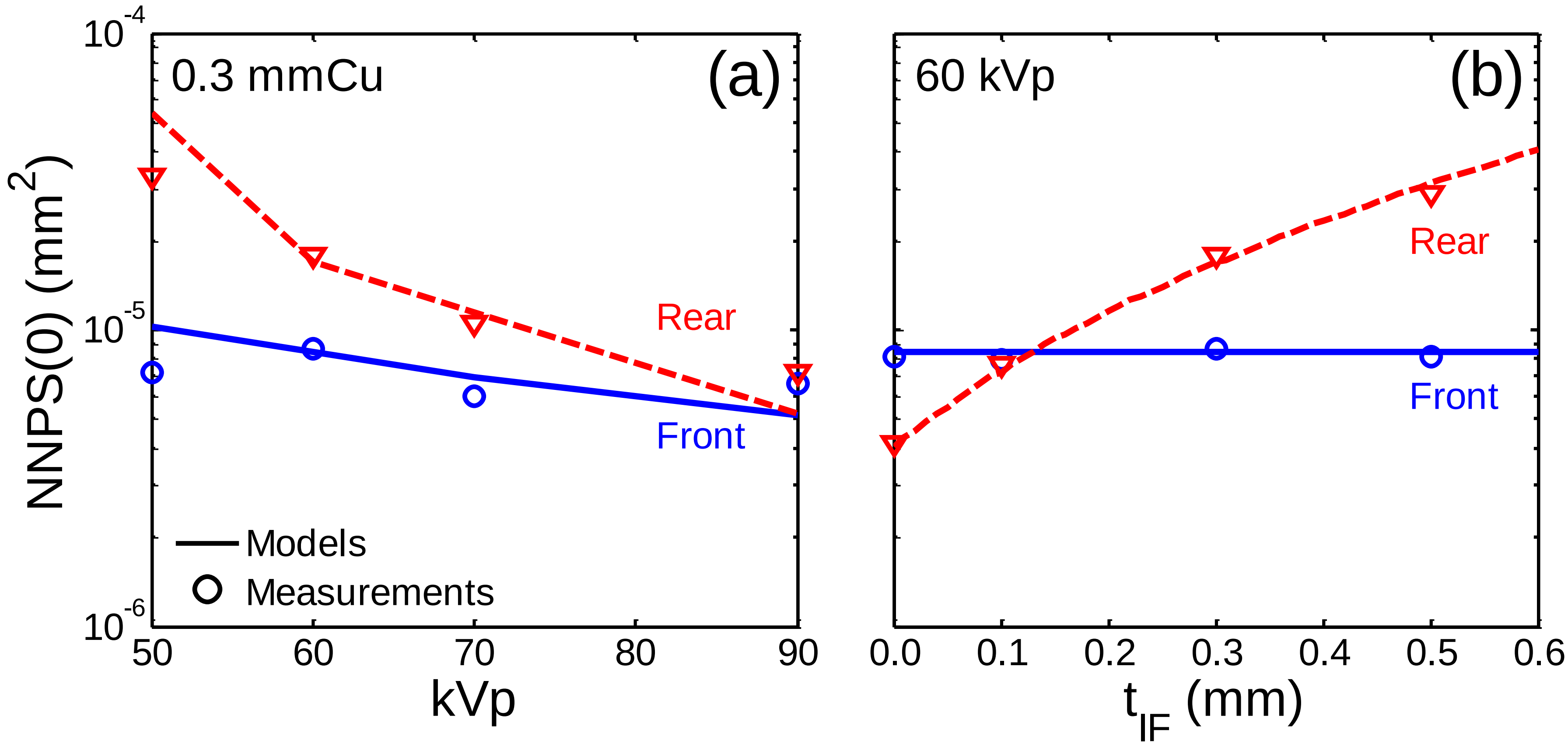
NNPS(0)

- Validation between measured in sandwich detector and CSA model
- $\mathrm{NNPS}(0) = \left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{MTF}_{\mathrm{pre}}^{2}(u,v)\mathrm{d}u\mathrm{d}v\right]^{-1}\left(\sigma_d^2/\bar{d}\right)^2 = A_{\mathrm{eff}}\left(\sigma_d^2/\bar{d}\right)^2$



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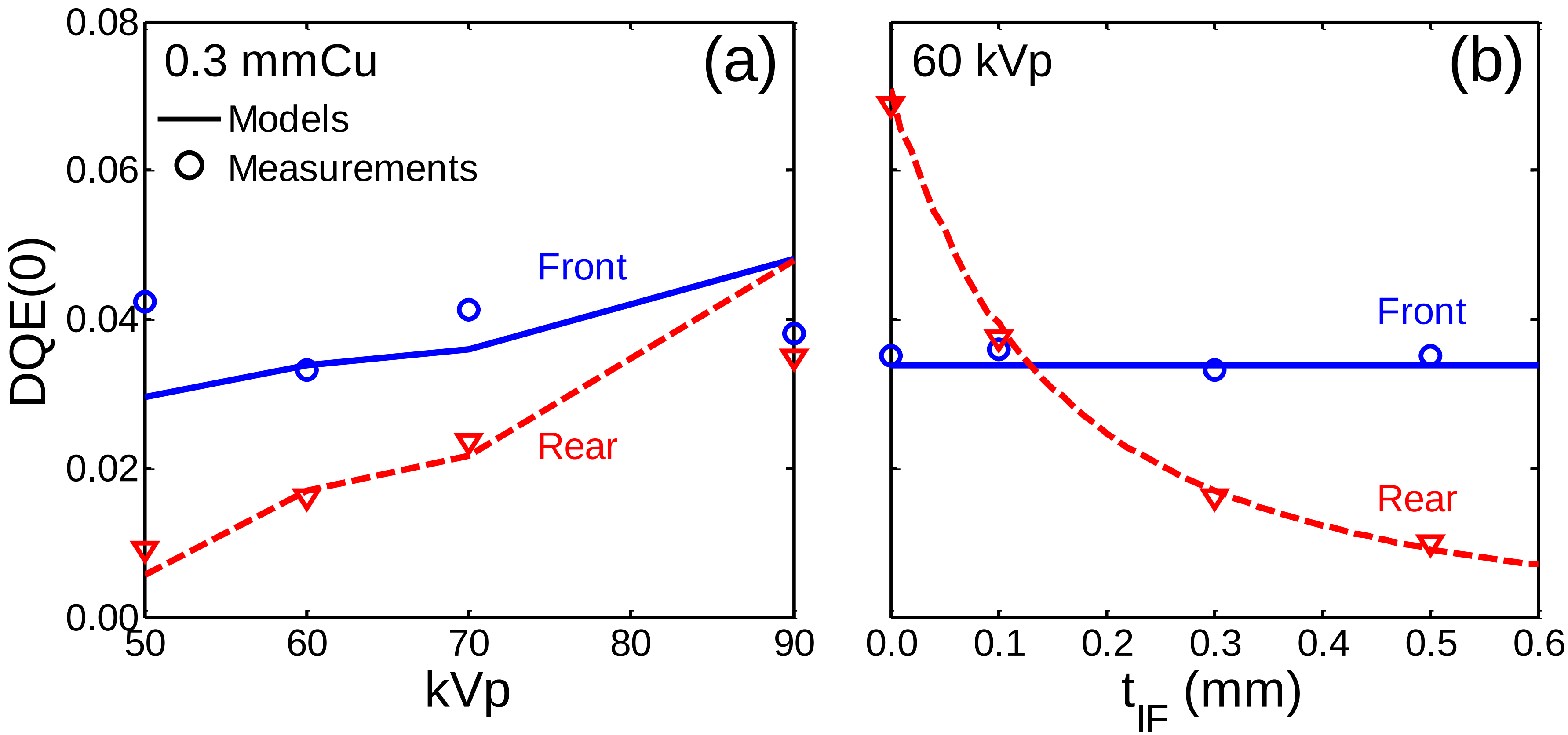
DQE(0)

- Validation between measured in sandwich detector and CSA model
- $\mathrm{DQE}(0) = \frac{1}{\bar{q}\mathrm{NPS}(0)/\bar{d}^2} = \frac{1}{\bar{q}\mathrm{NNPS}(0)}$



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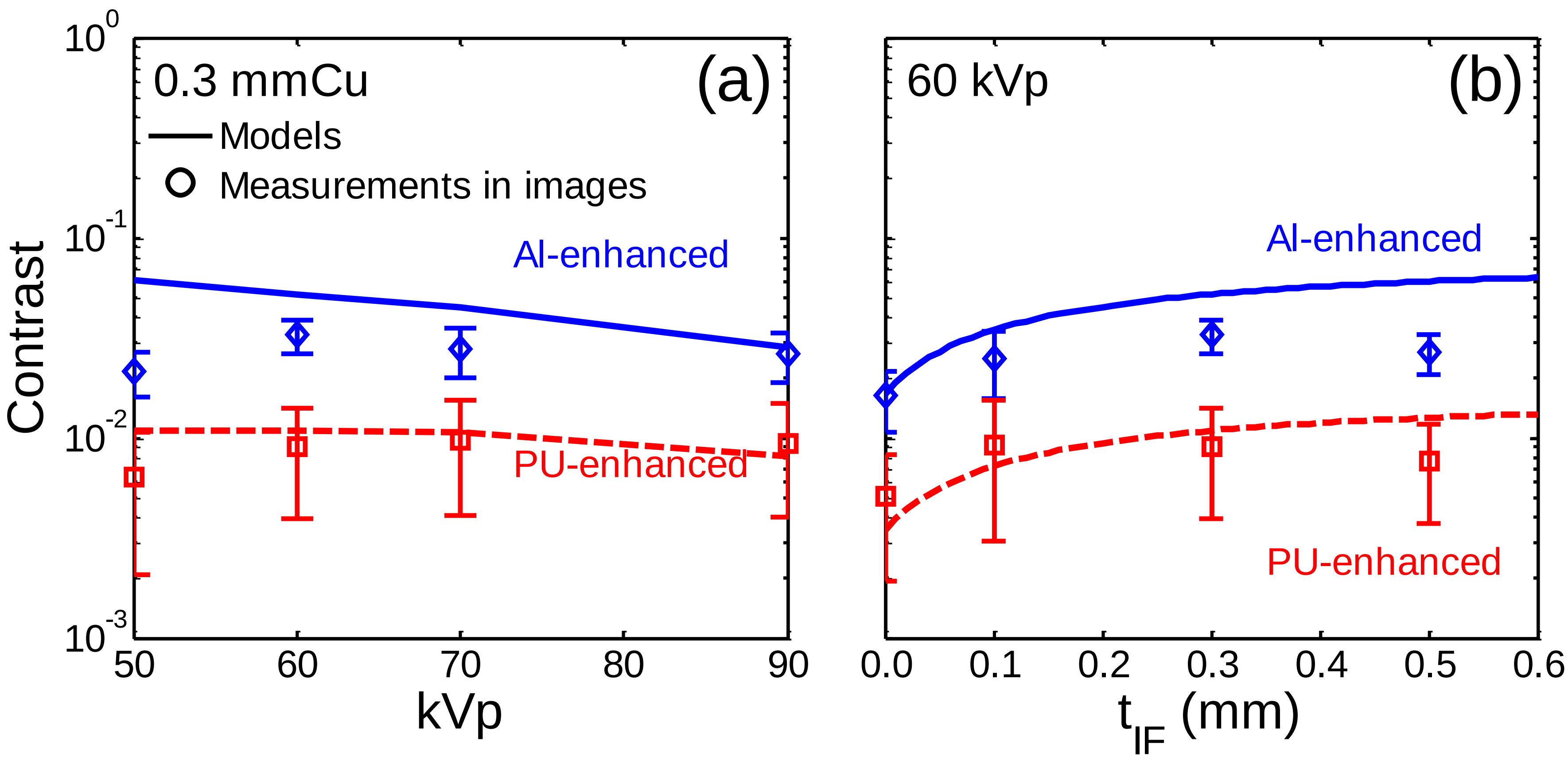
Contrast

- Contrast of single-shot dual-energy imaging with sandwich detector
- $C_j = \left| p_{jM}^{DE} - p_{\hat{j}M}^{DE} \right| = \left| \left(w_{\hat{j}} \Delta\mu_{jM}^{F} - \Delta\mu_{jM}^{R} \right) t_j + \left(w_{\hat{j}} \Delta\mu_{\hat{j}M}^{F} - \Delta\mu_{\hat{j}M}^{R} \right) t_{\hat{j}} \right|$



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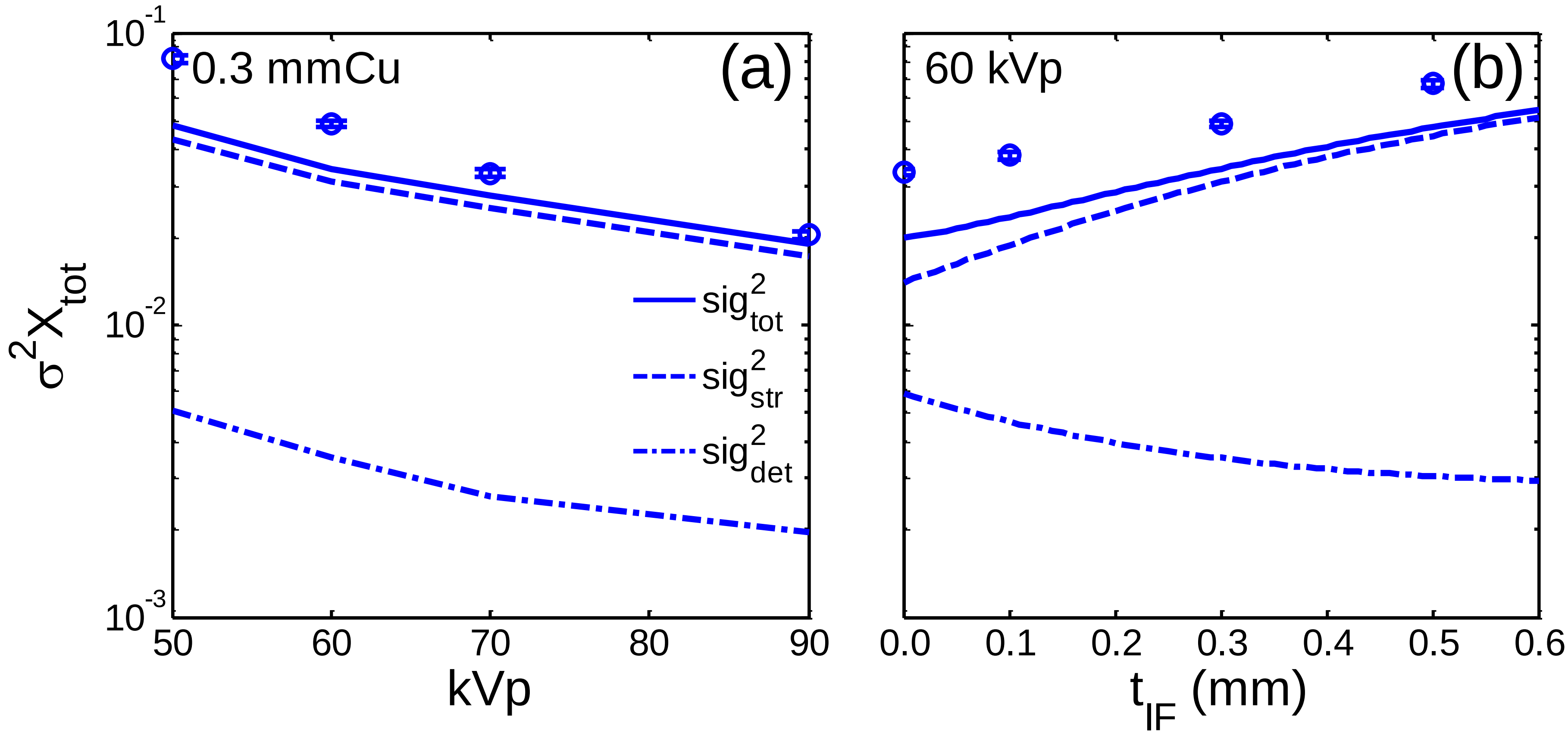
Noise

- Noise of single-shot dual-energy imaging with sandwich detector
- $\sigma_j^2 = \sigma_{j,\mathrm{det}}^2 + \sigma_{j,\mathrm{obj}}^2,\ \sigma_{j,\mathrm{obj}}^2 = w_{\hat{j}}^2\left(\sigma_{\mathrm{obj}}^F\right)^2 + \left(\sigma_{\mathrm{obj}}^R\right)^2$



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Noise with object noise

- Noise of single-shot dual-energy imaging with sandwich detector considering object noise

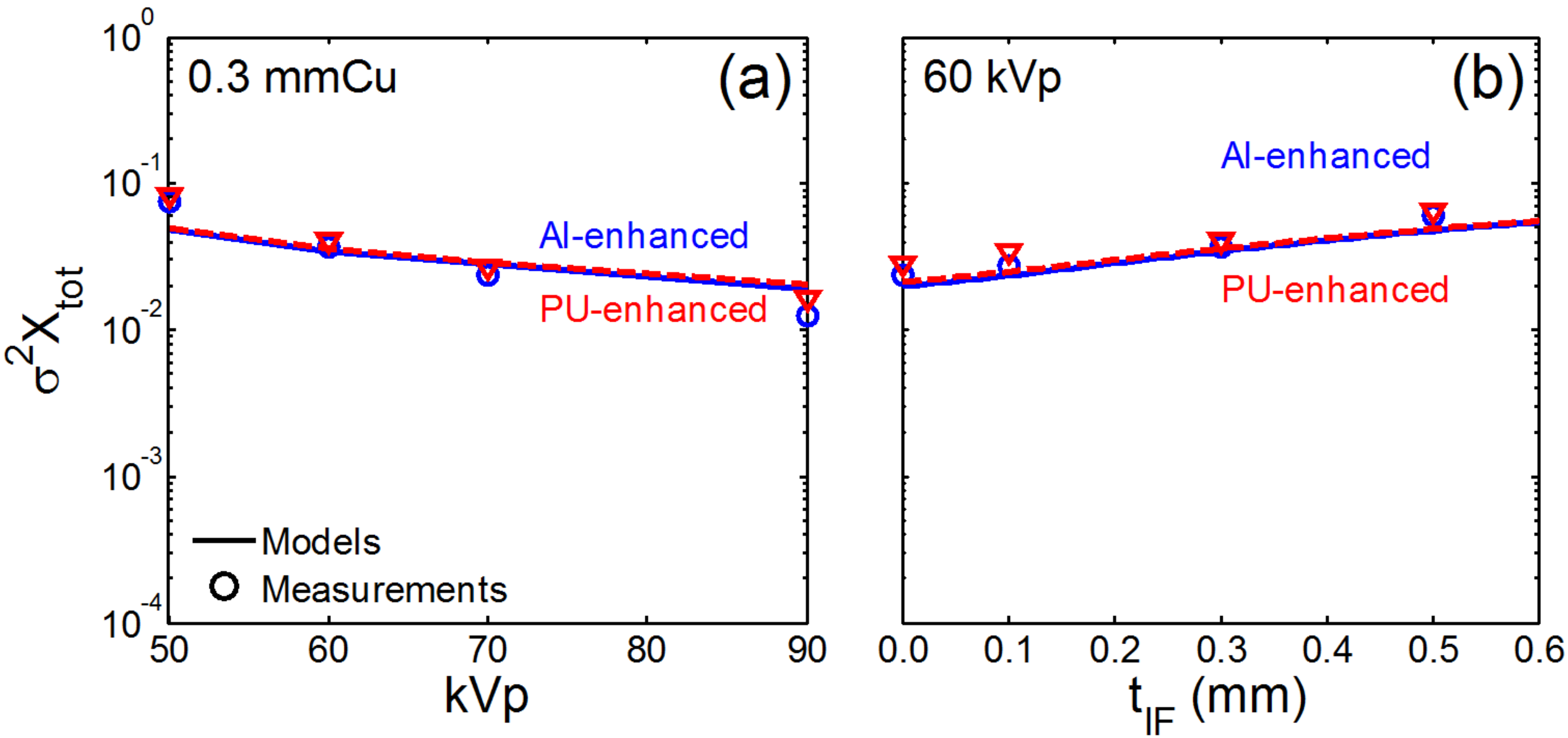

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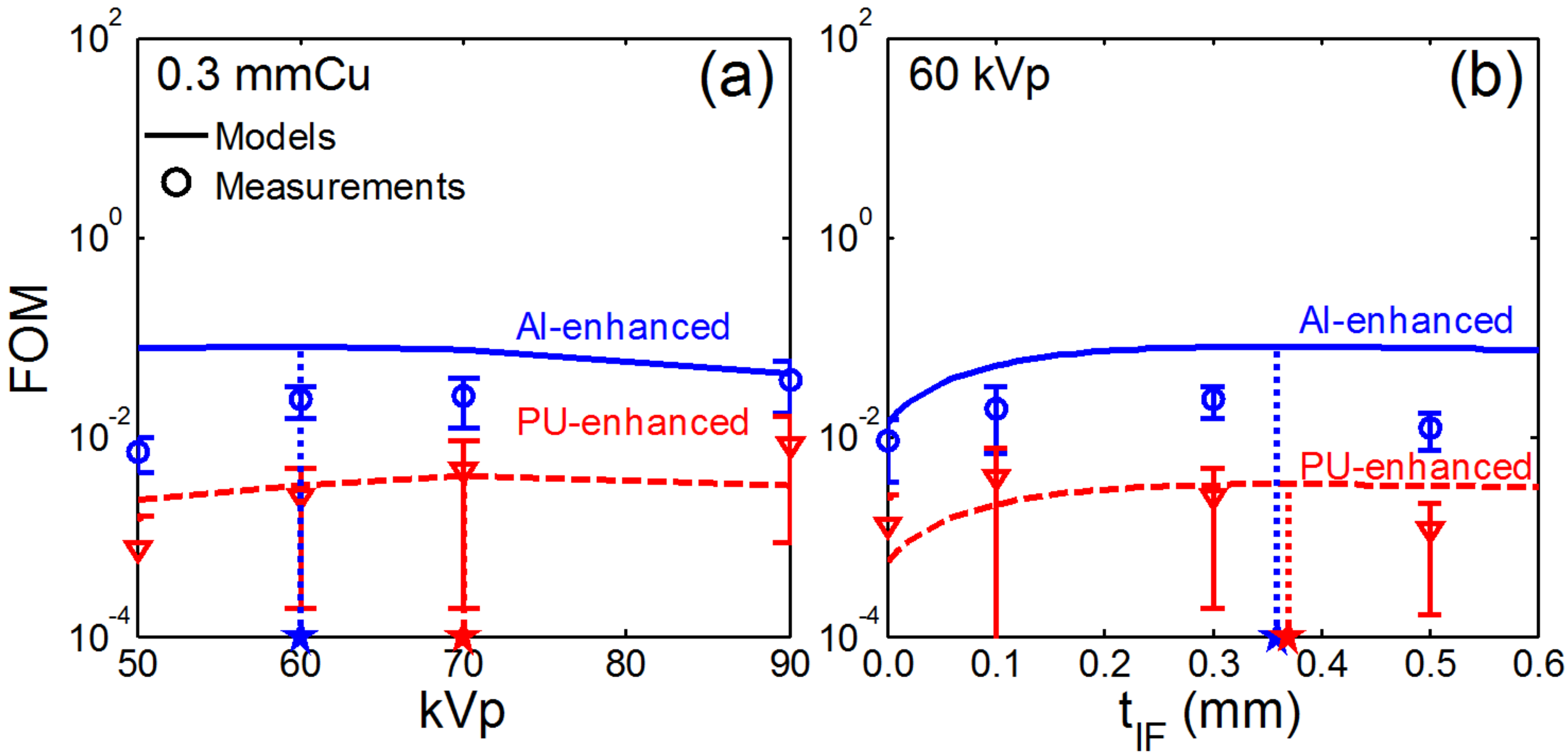
Figure of merit with object noise

- FOM of single-shot dual-energy imaging with sandwich detector considering object noise
- $\mathrm{FOM}_j = \frac{\mathrm{CNR}_j^2}{X} = C_j^2 \left[X \left\{ w_{\hat{j}}^2 \left(\left(\sigma_{\mathrm{det}}^F\right)^2 + \left(\sigma_{\mathrm{obj}}^F\right)^2 \right) + \left(\sigma_{\mathrm{det}}^R\right)^2 + \left(\sigma_{\mathrm{obj}}^R\right)^2 \right\} \right]^{-1}$



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Conclusion

- Noise components in dual-energy images were successfully computed and verified using zero-frequency components
- Using the linear cascaded system, we calculated the contrast and noise in dual-energy images, and developed the FOM model
- Successful validation using FOM model with anatomical structure noise
- The optimal design parameters of sandwich detectors for mouse imaging are tube voltage of 60 kVp and intermediate Cu filter thickness of 0.36 mm
- We plan to apply this model to further study the use of mammography and chest radiography imaging systems

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