An Accessible Analytical Approach to Characterize the Modulation Transfer Function of Fluoroscopic Systems

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ABSTRACT

Purpose: Improve accessibility of Modulation Transfer Function (MTF) metrics for implementing routine quality control (QC) of fluoroscopes.

Methods: A model-based method was devised involving one step: fit edge pixel data to a sigmoid function parameterized by α, the slope at inflection. With this method, MTF metrics MTF50, MTF20, MTF10, and MTFa scale linearly with α. This investigation only considered sigmoids with elementary derivatives and subsequent Fourier transforms. Five sigmoids met such criteria, here nicknamed Boltzmann, Gaussian, Gudermann, Laplacian, and Lorentzian. 2,212 fluoro loops of a tin swatch phantom were acquired by 18 fluoroscopes to assess model performance. The last frame of each loop was isolated, edge pixel data was obtained, and each sigmoid model was fit via Levenberg-Marquardt least-squares regression. Per fluoroscope, each model's precision was indicated by a low interquartile-range/median (IQR/M) for α.

Results: Four out of five sigmoid models had more precision than a numerical algorithm adapted from IEC 62220-1-3:2008. Across fluoroscopes, the mean IQR/M of each model's α were the following: Boltzmann: 0.34; Gaussian: 0.32; Gudermann: 0.36; Laplacian: 0.38; Lorentzian: 1.54. By comparison, the mean IQR/M of IEC MTF50 was 0.99.

Conclusion: The model-based method, particularly a Gaussian sigmoid, provides accessible spatial resolution measurement suited for routine fluoroscopic QC. The simplicity facilitates standardization, having less degrees of freedom in implementation than numerical approaches. Numerical approaches prioritize accuracy; the model-based method retains relative accuracy, excels in precision, and is more efficient for evaluation of clinical image quality.

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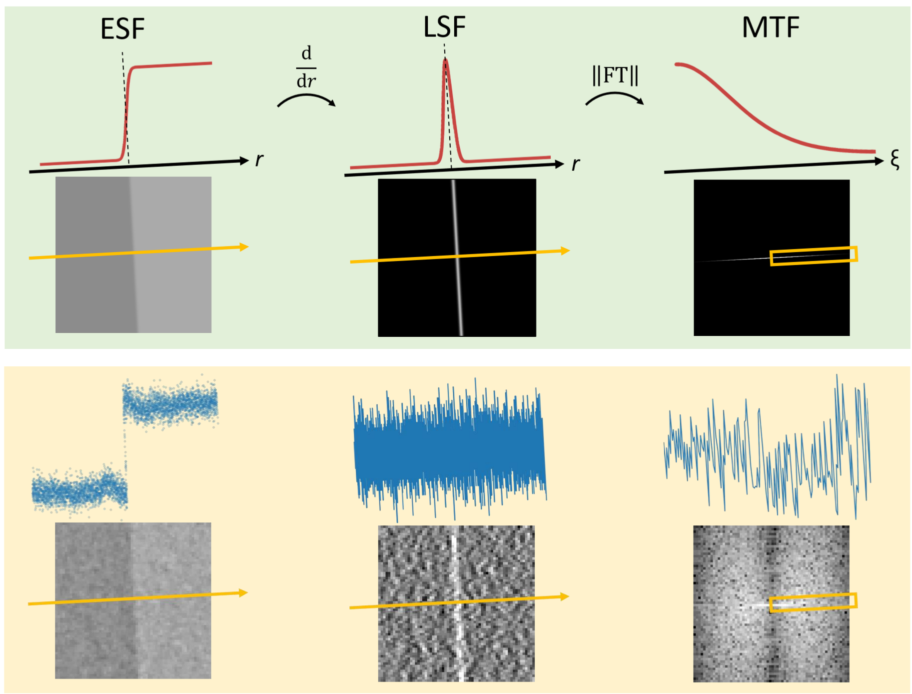
INTRODUCTION

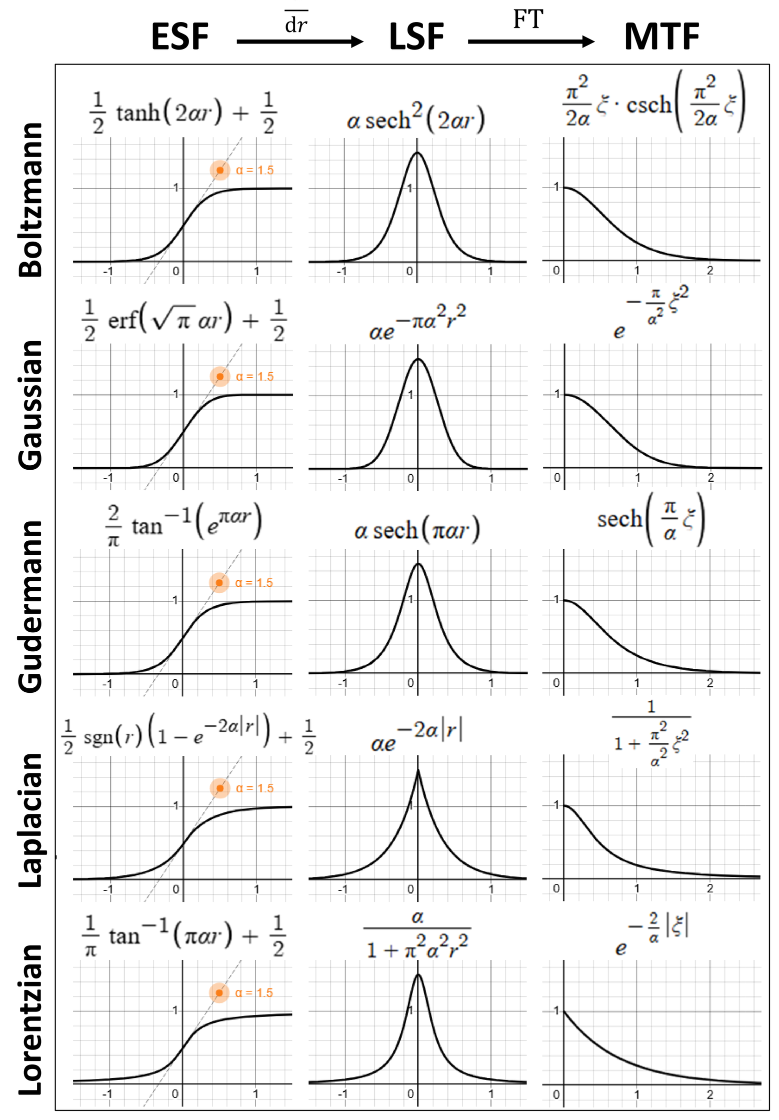
How can we make edge-based spatial resolution analysis accessible to noisy imaging modalities?



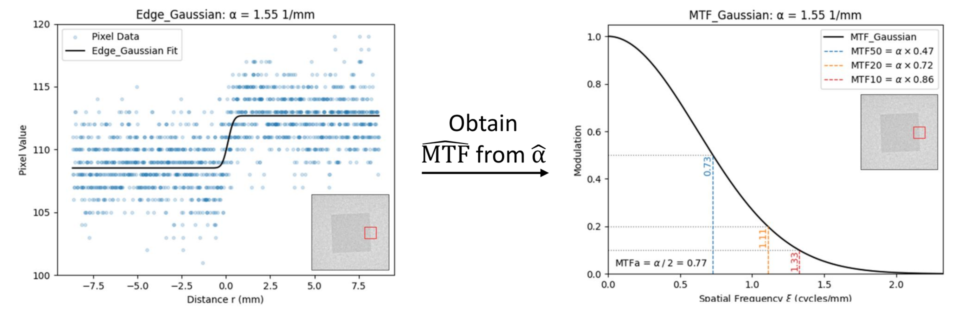
Curve fitting has been explored as an alternative to numerical algorithms in optics[1] and X-ray imaging.[2,3] Here, we demonstrate its practicality on isolated frames from fluoroscopic quality control loops.

METHODS AND MATERIALS

Five families of model edge spread, line spread, and modulation transfer functions were derived. Models are parameterized by α, the inflection slope of ESF.



Edge-normal pixel data were acquired with a tin foil phantom. Square ROIs (mean 43x43 px^2) on the last frame of loops from various fluoroscopes were used. Model sigmoids with shifting and scaling were fitted via least-squares for $\hat{\alpha}$. $\widehat{\mathrm{MTF50}}$, $\widehat{\mathrm{MTF20}}$, $\widehat{\mathrm{MTF10}}$, and $\widehat{\mathrm{MTFa}}$ were obtained as scalar multiples of $\hat{\alpha}$.



Performance of the regression method was compared against an adapted IEC algorithm[4] via precision and sensitivity of MTF measurements. Sensitivity was visually assessed as the difference between fluoroscopes' typical values. Precision was quantified as interquartile range/median.

Method performance was further compared with respect to image CNR and edge sampling geometry.

RESULTS

Regression demonstrates sensitivity and precision suitable for routine quality control.

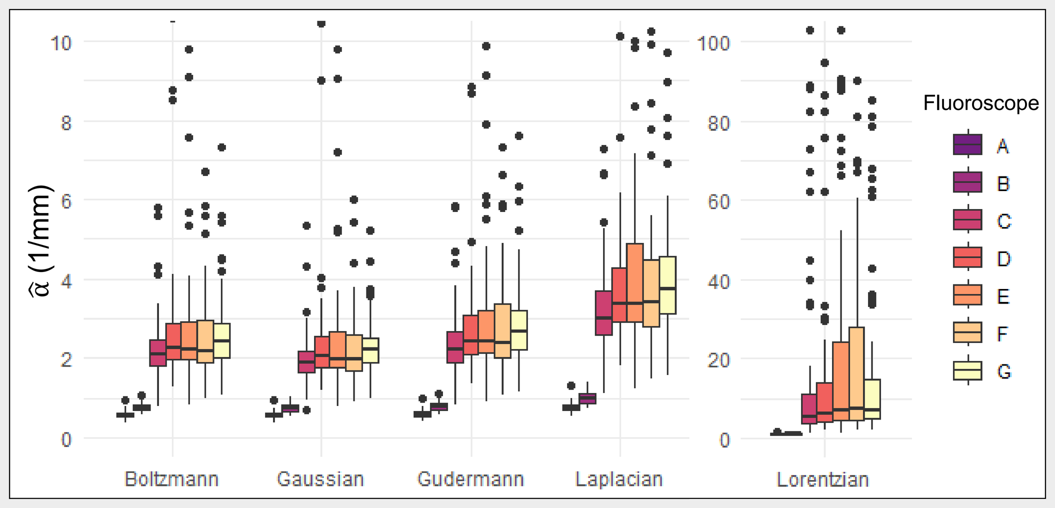


Figure 1. Fitted $\hat{\alpha}$ on seven fluoroscopes' images. Sensitivity is visible as differences in typical $\hat{\alpha}$ values of fluoroscopes A, B, and C–G. Per fluoroscope, n = 99–109.

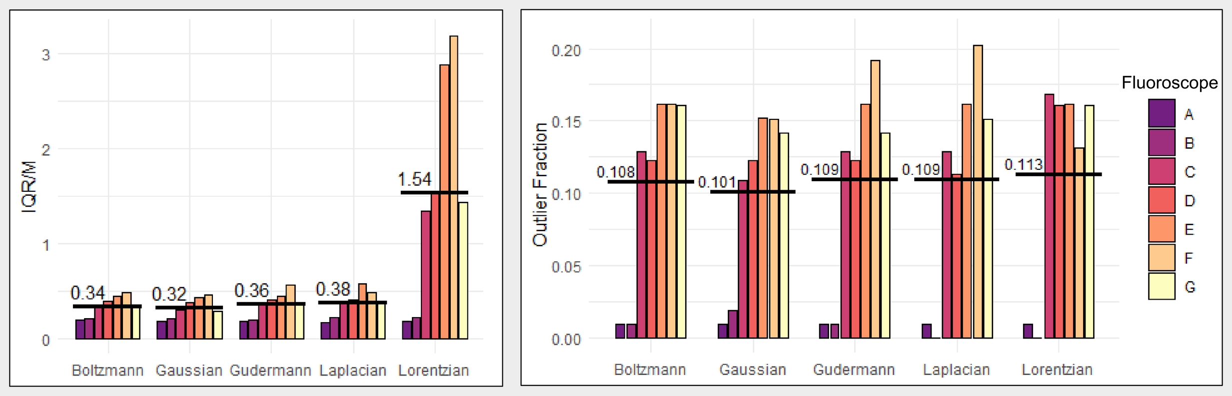


Figure 2. Regression performance on seven fluoroscopes. The Gaussian model demonstrated the best precision for α, given by the lowest mean IQR/M, and the highest measurement success rate, given by the lowest mean outlier fraction (> Q3 + 1.5 × IQR).

Regression is more sensitive and precise than the adapted IEC algorithm.

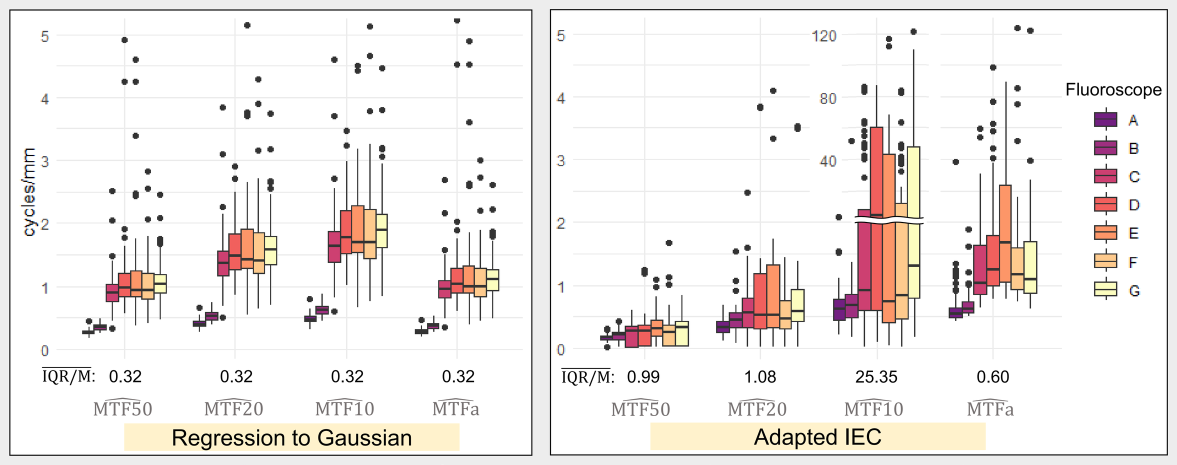


Figure 3. Measured MTF metrics from regression to the Gaussian model and the adapted IEC algorithm. Regression demonstrates more sensitivity than IEC for all metrics, visible as larger differences in typical values of fluoroscopes A, B, and C–G. Regression also demonstrates more precision than IEC for all metrics, given by lower mean IQR/M's.

Regression is more flexible than the adapted IEC algorithm regarding edge sampling.

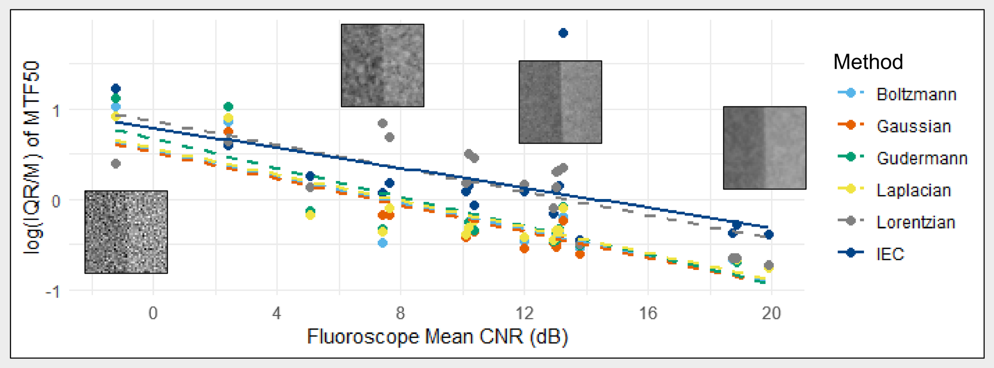
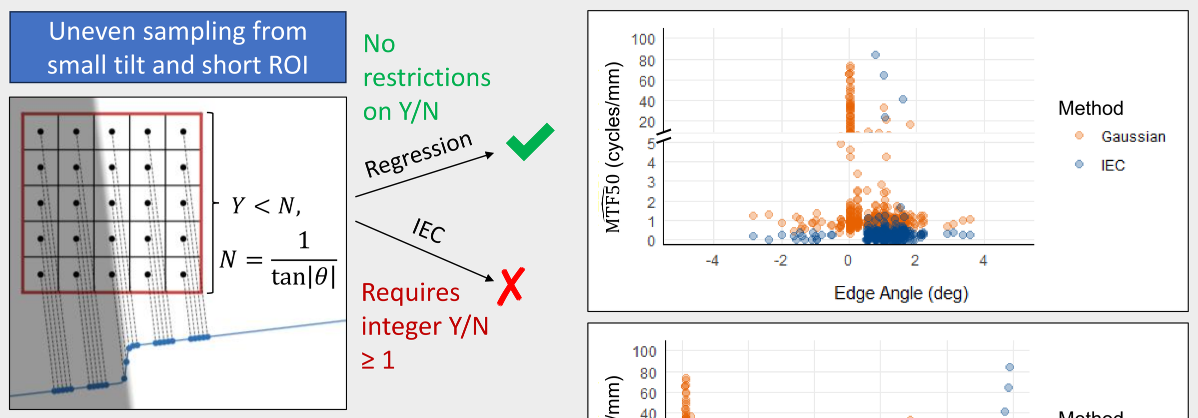


Figure 4. Four out of five models from the regression method generally show more tolerance to low contrast-to-noise ratios than the adapted IEC algorithm, given by lower IQR/M values. 18 fluoroscopes' images are represented (n = 13–297), hence 18 unique mean CNR values are represented. Lines to aid visualization are fitted by least squares.



$$\text{Phase Diversity} := 1 - \text{Coherence},$$

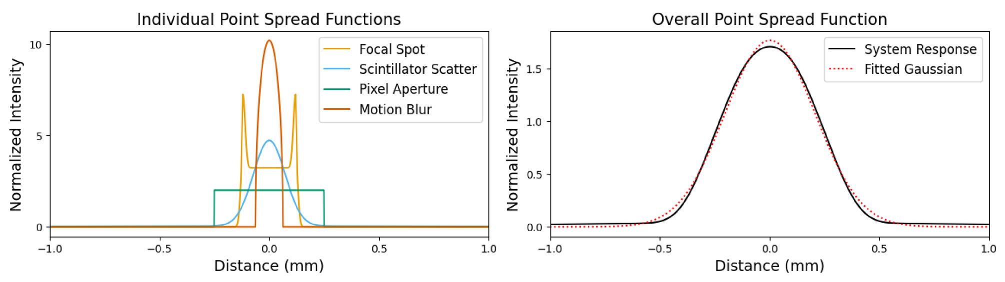
$$\text{Coherence} := \sqrt{\frac{6}{\pi^2}\sum_{k=1}^{\infty}\frac{|c_k|^2}{k^2}}, \quad c_k = \frac{1}{Y}\sum_{y=0}^{Y-1} e^{-j2\pi k\frac{y}{N}}$$

Figure 5. Regression does not enforce even sampling, unlike the IEC algorithm which uses discrete derivatives and DFTs. Sampling evenness was quantified as phase diversity, defined as the complement of a weighted quadrature sum of Fourier series coefficients of the sampling distribution. Scatter plots aggregate fluoroscope C–G $\widehat{\mathrm{MTF50}}$ from Figure 3. The IEC method omits 183/517 images with insufficient edge length given the small angle.

DISCUSSION

The Institute of Physics and Engineering in Medicine (IPEM) encourages quantitative spatial resolution testing,[5] but routine QC programs often neglect it or rely on visual assessment. This may be due to the burden of data preparation and complex algorithm steps. Different ways to implement each step make standardization difficult. Additionally, differentiation amplifies image noise, thus reducing the reliability of MTF metrics, especially MTF10. The regression method bypasses these burdens by reducing computation steps and image noise influence.

A theoretical rationale exists for broad application of the Gaussian model. The Lindeberg Central Limit Theorem dictates that contributions of many independent random imaging variables towards the system PSF, such as focal spot size, scintillator scatter, pixel binning, and motion blur, all convolve towards Gaussianity on pre-processed images.



This study used "For Presentation" routine daily QC images, unaltered prior to analysis. High outlying $\hat{\alpha}$ can result from minimizing sum of squared residuals between monotonic sigmoids and sharpened edge data. The Gaussian model was most robust against this, as it is most platykurtic. Low CNR and low phase diversity also introduce variability, though this impacted the regression method less than the adapted IEC algorithm. Outlier influence can be mitigated by taking the harmonic mean of several $\hat{\alpha}$.

Current efforts in the curve fitting space focus on pre-processed image characterization. However, most medical facilities can only access post-processed images for routine QC. Further work is investigating if advanced ESF modeling, accounting for digital edge sharpening, improves measurement precision whilst retaining ease of implementation. Additionally, the ISO algorithm is being examined.

The regression method does not aim to replace the original IEC standard or other numerical approaches when accuracy of the MTF is prioritized, or frame-averaged images with high CNR are used, such as in commissioning and annual testing.

CONCLUSIONS

The simplicity of the regression method reduces implementation error compared to numerical approaches. The robustness against noise results in precision and sensitivity suitable for routine QC.

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