Quantifying Lesion Contrast-to-Noise Ratio in Simulated Digital Mammography Using the VICTRE Pipeline

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PURPOSE / OBJECTIVES

Contrast-to-noise ratio (CNR) is commonly used to quantify lesion conspicuity in mammography, yet measured CNR depends on both imaging conditions and ROI selection methodology.

The purpose of this study was to quantify lesion CNR in simulated digital mammography using the VICTRE[1,2] framework and evaluate the effects of:

• Lesion size • Lesion density • Tube potential • Scatter • ROI methodology

METHODS

VICTRE Phantom Generation[3]

- Four anthropomorphic breast phantoms
- Density categories spanning fatty to extremely dense
  - 20% (fatty/low), 40% (mid-low), 60% (mid-high), 80% (extremely dense/high)
- Single spiculated mass inserted at fixed location

Lesion Parameters[4]

- Size (alpha): 1.0 – 4.0 mm (1.0, 1.5, 2.0, 2.5, 3.0, 4.0)
- Lesion Density: 1.06 – 1.25 g/cm^3 (1.06, 1.10, 1.15, 1.20, 1.25)

Acquisition Parameters[5-7]

- Tube Potential: W/Rh - 24 and 40 kVp
- Projection Type: Primary and Primary + Scatter
- Exposure Normalization informed by clinical AEC behavior

Image Representations

- DICOM (for processing) reconstructed projection images
- Air-normalized, log-transformed attenuation images (µx RAW)

ROI Strategies

- TOP: Background (BG) ROI positioned superior to the lesion
- LR: BG ROI positioned lateral to the lesion with geometry scaled to lesion size
- LR-fixed: BG ROI positioned lateral to the lesion using fixed geometry across all lesion sizes
- LC-BG: Lesion-centered BG ROI generated locally around the lesion while excluding lesion pixels
- ROI locations were held constant across imaging energies and scatter conditions to enable direct comparison of CNR measurements.

CNR Equation

- $CNR = \frac{|S_{lesion} - S_{Background}|}{\sigma_{background}}$
- where S_{lesion} and $S_{background}$ are the mean lesion and background signals, respectively, and $\sigma_{background}$ is the background standard deviation.

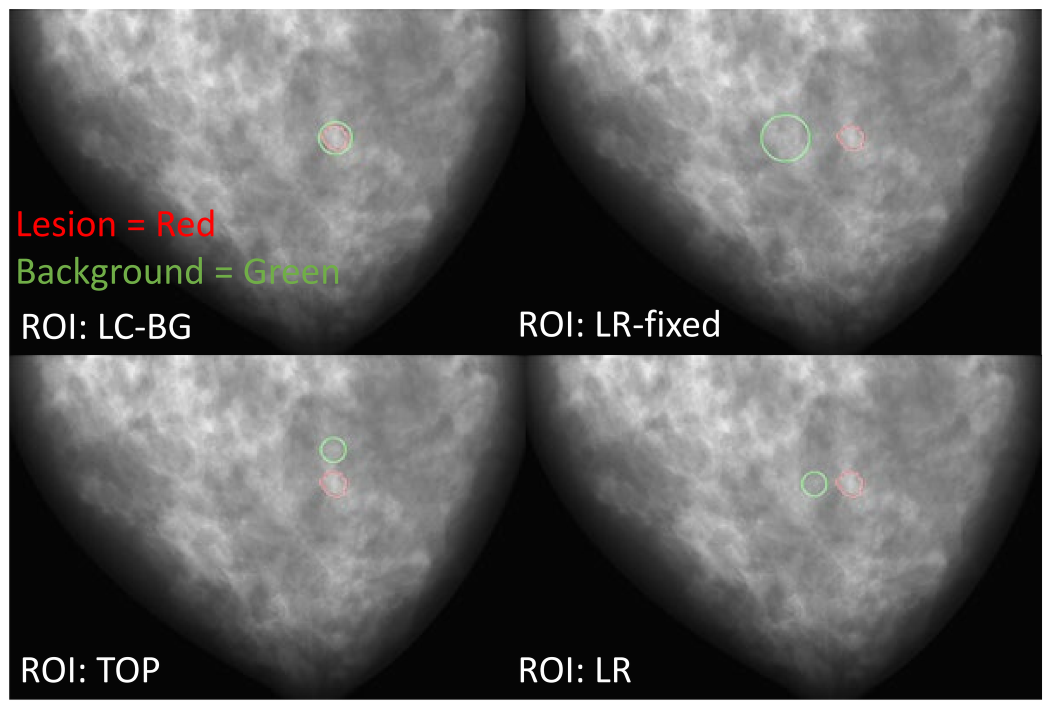

Figure 1. Representative examples of the four ROI strategies used for lesion CNR estimation. Lesion ROIs (red) and background ROIs (green) are shown for the TOP (superior background), LR (lateral lesion-scaled background), LR-fixed (lateral fixed-geometry background), and LC-BG (lesion-centered background) methodologies.

RESULTS

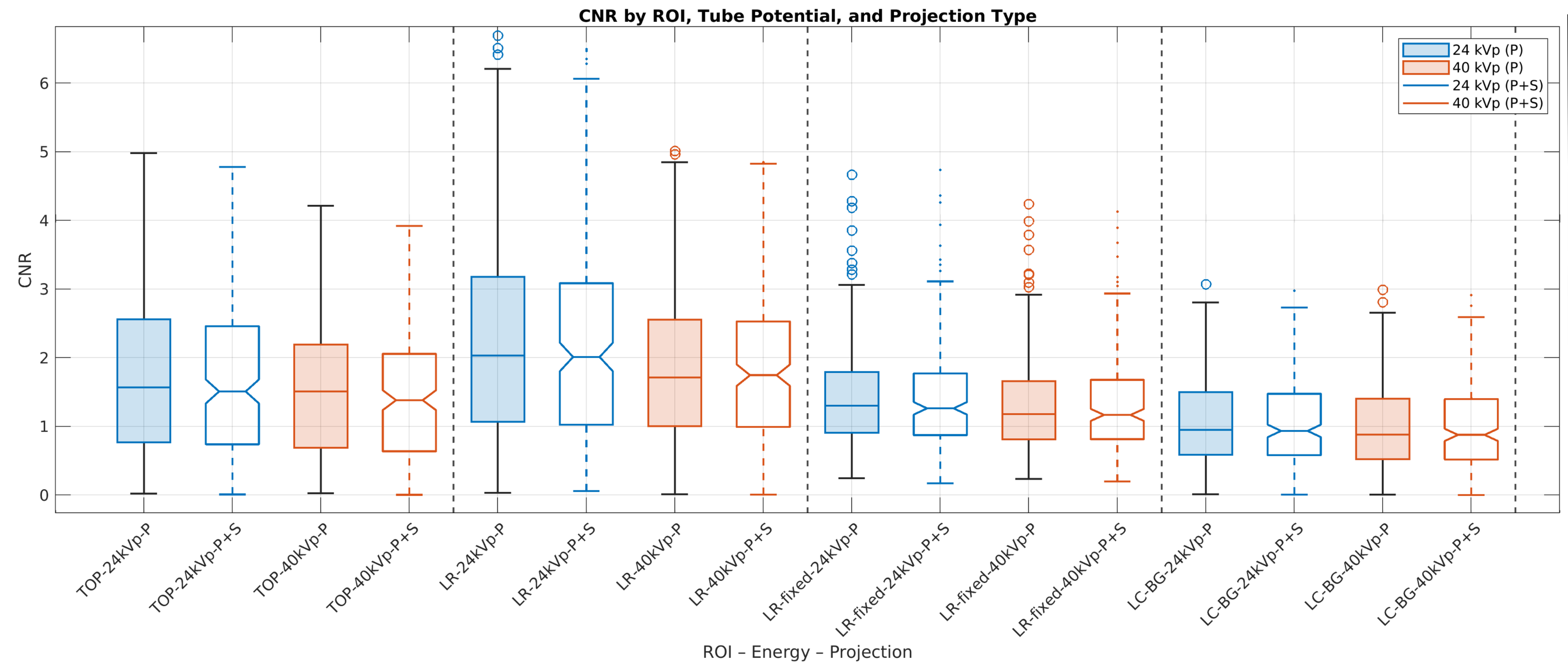

Figure 2. Distribution of lesion CNR by ROI methodology, tube potential, and projection type. Boxplots showing the combined influence of ROI methodology, tube potential, and projection type on lesion CNR. CNR values reflect aggregate behavior across all lesion sizes, lesion densities, breast-density categories, and image formats included in the study. This figure provides a global view of lesion conspicuity under simulated mammographic imaging conditions. [P = Primary; P+S = Primary + Scatter]

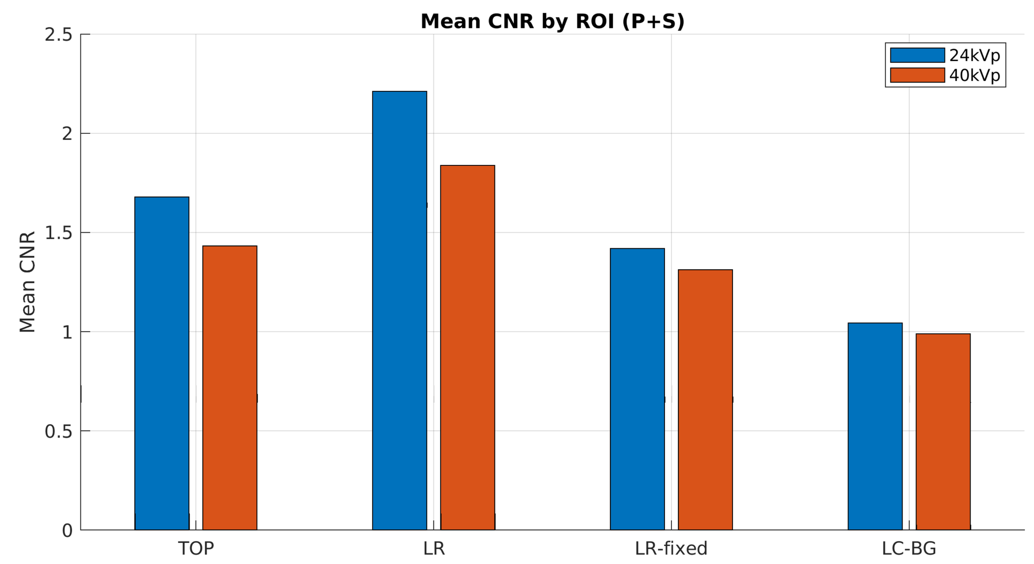

Figure 3. Mean lesion CNR by ROI methodology and tube potential for primary-plus-scatter projections. Bar plot showing mean lesion CNR for each ROI strategy (TOP, LR, LR-fixed, and LC-BG) for both 24 kVp and 40 kVp primary-plus-scatter projections. Values combine all lesion sizes, lesion densities, breast-density categories, and image formats. This figure highlights differences in measured CNR between ROI methodologies and imaging energies.

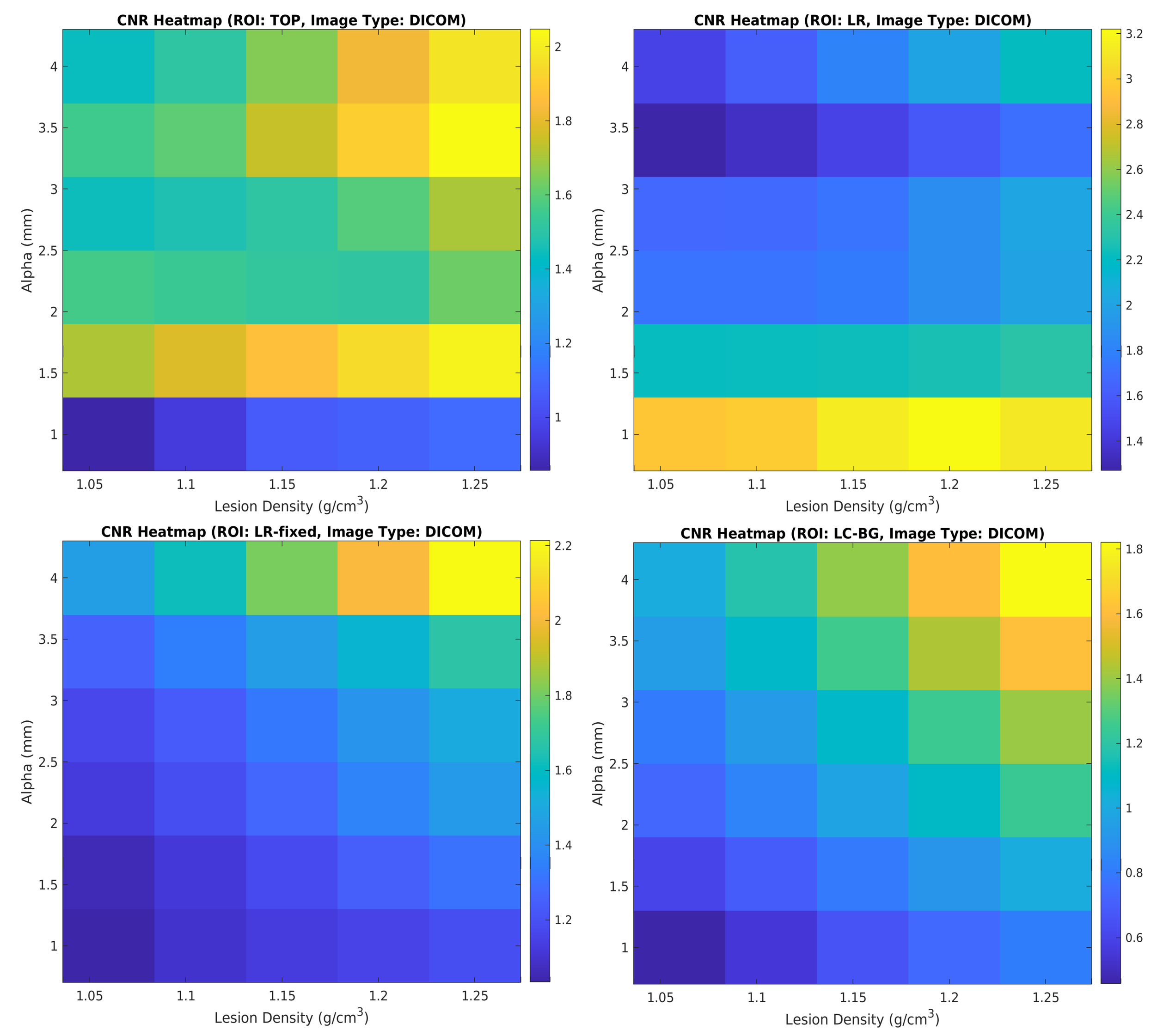

Figure 4. Heatmaps of lesion CNR as a function of lesion size and lesion density across ROI methodologies. Four heatmaps arranged in a 2×2 grid corresponding to TOP, LR, LR-fixed, and LC-BG ROI strategies. Each heatmap depicts lesion CNR as a function of lesion size (alpha) and lesion density for primary-plus-scatter projections. Consistent increases in CNR are expected with increasing lesion size and lesion density; deviations from these trends illustrate the influence of ROI selection and local anatomical background variability on measured lesion conspicuity.

Table 1. Paired statistical comparisons of lesion CNR.

Comparison	ROI	Mean ΔCNR	p-value
(Block 1: primary+scatter; paired with each ROI strategy)			
Energy: 24 vs 40 kVp	TOP	0.248	<0.001 (n=480)
Energy: 24 vs 40 kVp	LR	0.372	<0.001 (n=480)
Energy: 24 vs 40 kVp	LR-fixed	0.107	<0.001 (n=480)
Energy: 24 vs 40 kVp	LC-BG	0.053	<0.001 (n=480)
(Block 2: primary+scatter; energies and image types combined)			
ROI: TOP vs LR	-	-0.469	<0.001 (n=960)
ROI: TOP vs LR-fixed	-	0.190	<0.001 (n=960)
ROI: TOP vs LC-BG	-	0.539	<0.001 (n=960)
ROI: LR vs LR-fixed	-	0.660	<0.001 (n=960)
ROI: LR vs LC-BG	-	1.008	<0.001 (n=960)
ROI: LR-fixed vs LC-BG	-	0.348	<0.001 (n=960)
(Block 3: energies and image types combined)			
Projection Type: P vs P+S	TOP	0.091	<0.001 (n=960)
Projection Type: P vs P+S	LR	0.029	<0.001 (n=960)
Projection Type: P vs P+S	LR-fixed	0.015	<0.001 (n=960)
Projection Type: P vs P+S	LC-BG	0.009	<0.001 (n=960)

Notes: ΔCNR indicates paired mean CNR difference (positive favors the first condition). P = primary-only; P+S = primary-plus-scatter. ROI strategies: TOP (superior), LR (lateral, lesion-scaled), LR-fixed (lateral, fixed geometry), and LC-BG (lesion-centered background). All tests were paired; n indicates the number of paired observations.

CONCLUSIONS

- Lesion CNR demonstrated strong dependence on **imaging energy, scatter conditions,** and **ROI methodology**.
- **Lower energy** (24 kVp) and **primary-only projections** consistently produced higher CNR than higher-energy and scatter-inclusive acquisitions.
- **LR-fixed** and **LC-BG ROI methodologies** demonstrated the most consistent CNR trends **with increasing lesion size** and **lesion density**, consistent with expected physical behavior.
- **ROI selection** significantly influenced measured CNR values and trend stability, highlighting the importance of **standardized** CNR assessment methods.
- **Lesion-centered background sampling (LC-BG**) provided a reproducible and physically local approach for simulation-based lesion conspicuity evaluation.
- These findings establish a quantitative baseline for future **image-quality assessment** and **optimization studies** using the VICTRE simulation framework.

FUTURE WORK

- Investigate the relationship between lesion CNR and task-based detectability metrics, including model-observer detectability index (d').
- Quantify the influence of target/filter combinations and beam quality on lesion conspicuity across varying breast compositions.
- Expand the phantom cohort to better characterize the effects of breast density, lesion location, and local anatomical background variability on lesion visibility.
- Extend analyses to microcalcification clusters and other clinically relevant lesion detection tasks.
- Apply these findings to guide optimization and evaluation of energy-domain image translation methods in mammography.

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REFERENCES

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