Image Quality Characterization of On-Board kV-CBCT Systems on Modern Linear Accelerator Units

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INTRODUCTION

The integration of on-board kilovoltage (kV)-cone-beam computed tomography (CBCT) imaging systems on modern radiotherapy treatment machines has been a crucial component in the development and further advancement of effective image-guided radiotherapy (IGRT) and (more recently) offline/online adaptive radiotherapy (ART) processes. While CBCT imagers have historically demonstrated inferior imaging performance compared to conventional CT units, recent advancements in both software and hardware components have greatly enhanced the imaging capabilities offered by such on-board systems.

The objective of this multi-institutional study was to quantitatively evaluate and compare the imaging performance of various on-board kV-CBCT systems implemented on modern C-arm and O-ring linear accelerator units and to comprehensively assess performance of a novel kV-CBCT solution on a common C-arm treatment machine.

METHODS

On-board kV-CBCT imaging systems evaluated include separate C-arm units with an original 40×30cm^2 detector panel (C-4030) and an updated 43×43cm^2 panel (C-4343) and separate O-ring units with an original 43×43cm^2 panel (O-4343) and an updated 86×43cm^2 panel (O-8643). The O-8643 system was assessed in both IGRT and planning (CBCTp) modes. The image quality phantom was scanned across all default acquisition modes available on each system, and images were reconstructed using both standard Feldkamp-Davis-Kress (FDK) filtered-backprojection and iterative reconstruction (IR) algorithms. All images were reconstructed with the default 2mm slice thicknesses with the exception of the CBCTp mode scans from the O-8643 system, which are reconstructed with a 3mm interval by default. Image quality metrics including noise, uniformity, low-contrast visibility (LCV), spatial resolution, geometric distortion, and CT number linearity were evaluated via semi-automated Python scripting developed with utilization of the *Pylinac* library.

Additionally, the C-4343 on-board imaging system was further characterized through comprehensive assessment of the aforementioned image quality metrics derived from scans acquired with variation of the available user-adjustable imaging parameters, including the imaging energy (kVp), exposure (mAs), reconstruction algorithm, convolution filter, noise suppression level, slice thickness, and radial field-of-view (FOV).

RESULTS

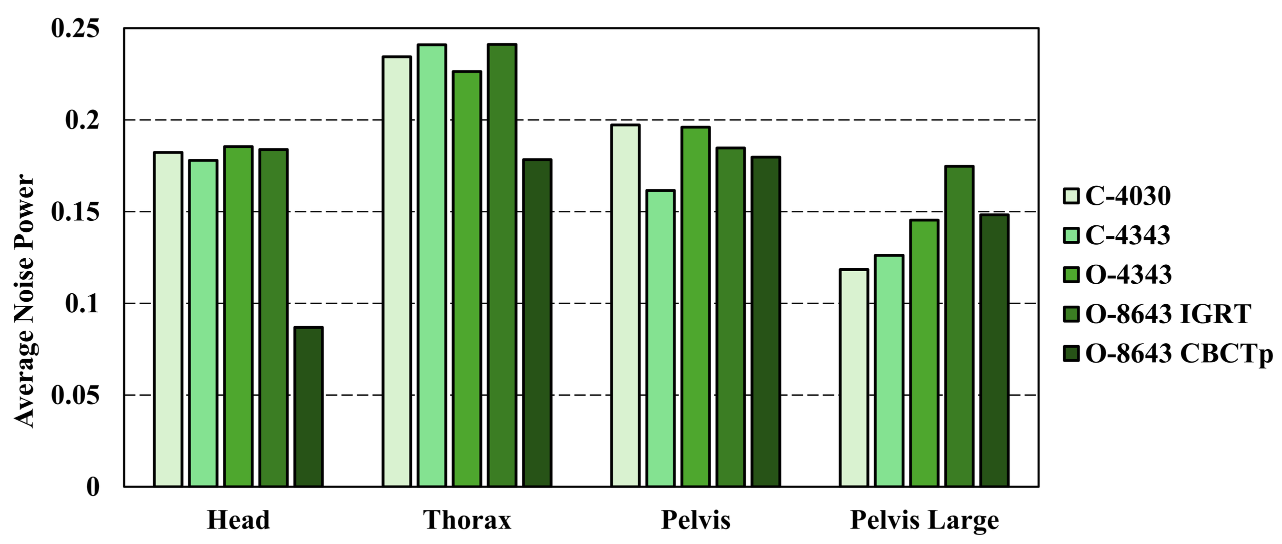

Figure 1 – Average power of the noise power spectrum (NPS) for each default acquisition mode on each imaging system, considering only the *iterative* (iCBCT) reconstruction algorithm. The NPS provides a more complete description of the noise than the standard deviation (as it characterizes the noise "texture"). In practice, lower values indicate less "noisy" images visually.

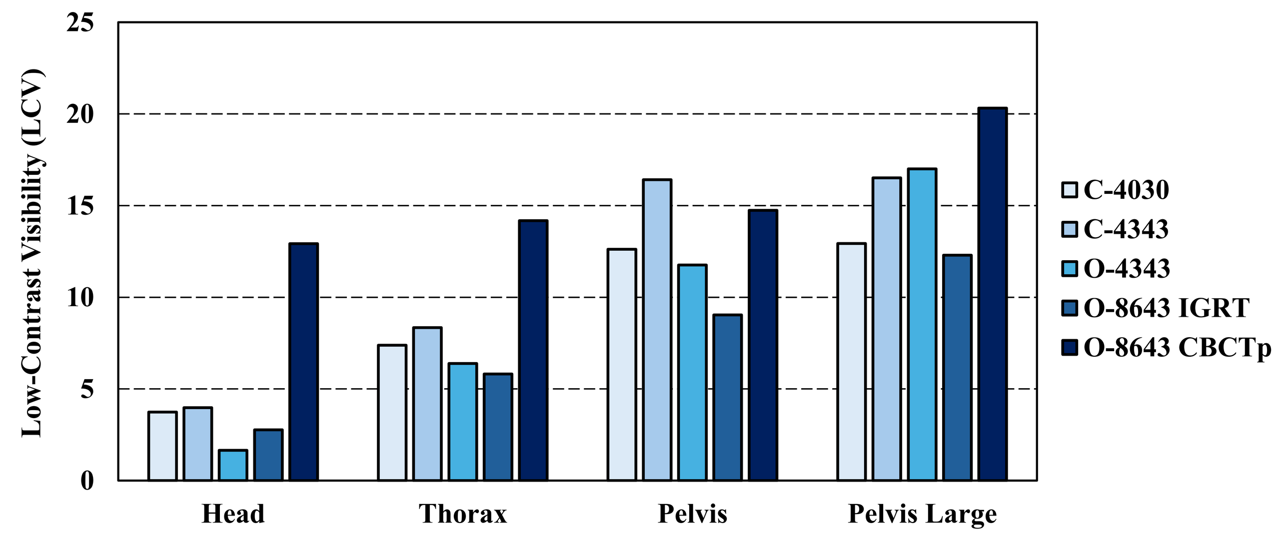

Figure 2 – Low-contrast visibility (LCV) for each default acquisition mode on each imaging system, considering only the *iterative* (iCBCT) reconstruction algorithm. For this LCV metric, higher values indicate improved low-contrast visualization.

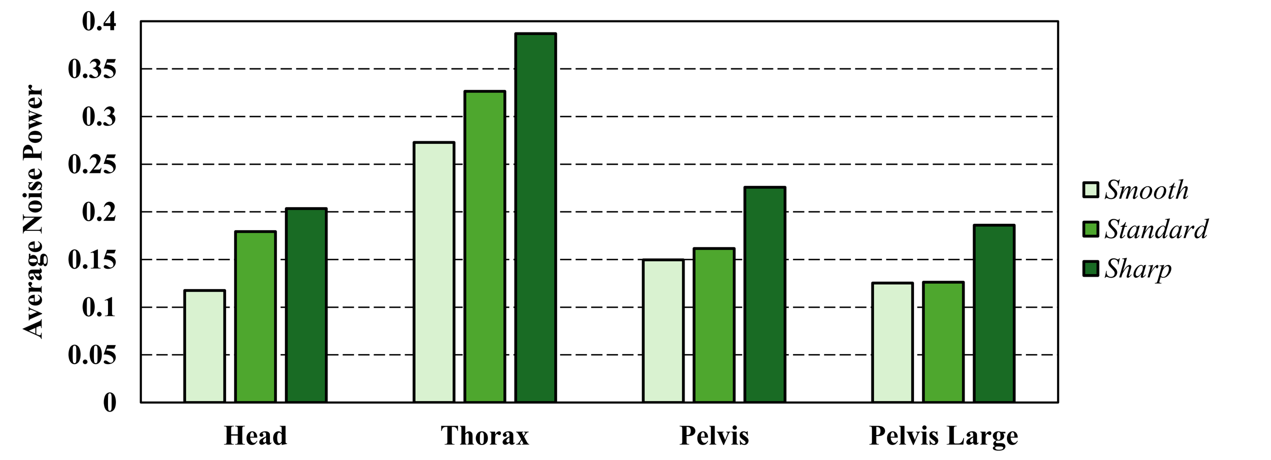

Figure 3 – Average power of the noise power spectrum (NPS) for each default acquisition mode on the C-4343 system for the *Smooth*, *Standard*, and *Sharp* convolution filters. Of note, the *Thorax* protocol utilizes the standard FDK reconstruction by default (resulting in increased noise overall compared to the other default modes).

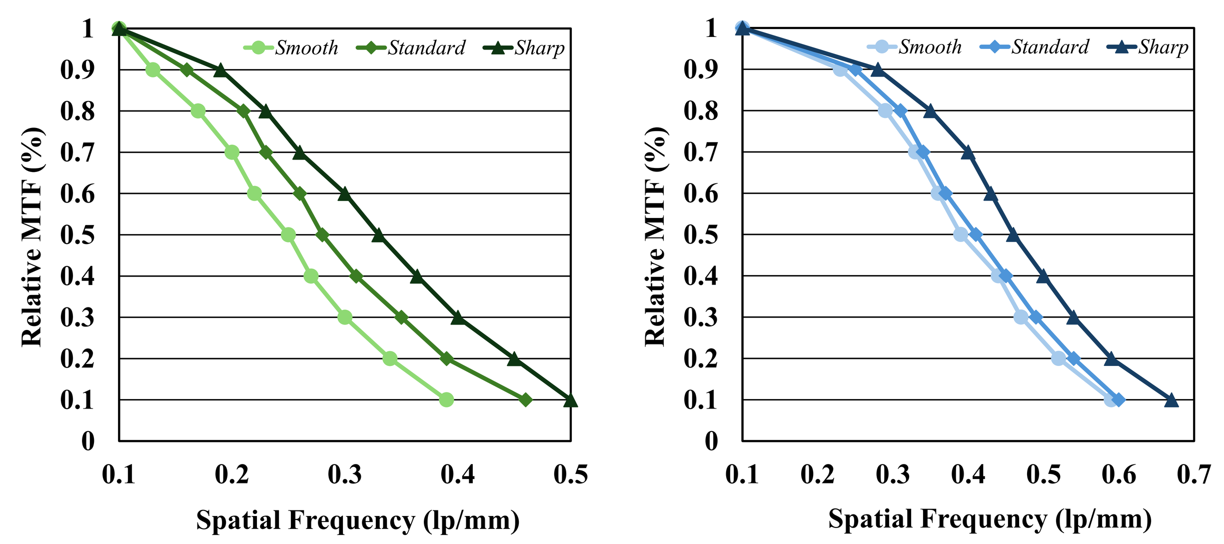

Figure 4 – Relative modulated transfer function (MTF) values for the default *Thorax* acquisition mode (left) and *Head* acquisition mode (right) on the C-4343 system for the *Smooth*, *Standard*, and *Sharp* convolution filters.

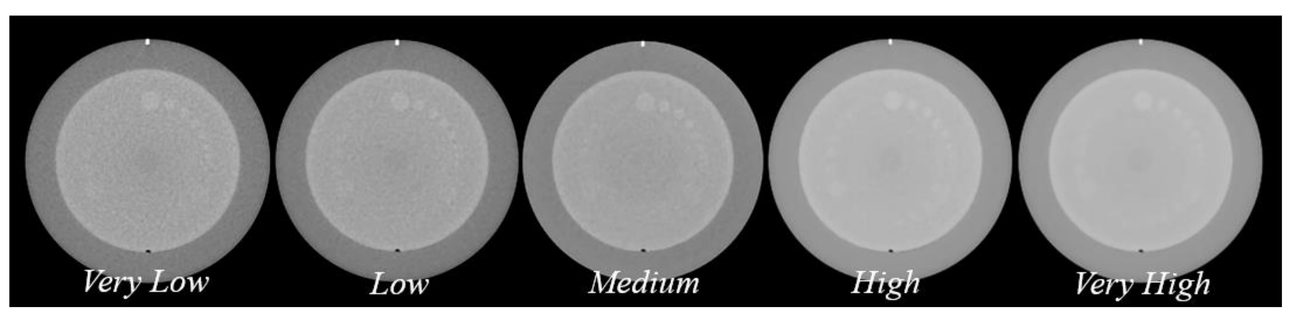

Figure 5 – Axial CBCT slices of the image quality phantom with the various noise suppression levels applied for the *Pelvis* acquisition mode on the C-4343 system.

Multi-Institutional, Multi-System Comparison

- Overall, noise levels were lowest for O-8643 CBCTp mode, while comparable noise levels were observed for the remaining systems (*Figure 1*).
  - It is necessary to note that a portion of the noise reduction for O-8643 CBCTp mode was a result of the increased slice thickness compared to the other systems evaluated (3mm vs. 2mm), as image noise is inversely proportional to this parameter.
  - IR noticeably reduced noise compared to the standard FDK reconstruction for all systems.
- Uniformity was generally best for O-8643 (both modes), while C-4343 and O-4343 demonstrated improved uniformity compared to C-4030.
  - Apart from O-4343 (which displayed slight "capping" artifact), mild "cupping" artifact was generally present across the various acquisitions on all systems.
- While LCV was best for O-8643 CBCTp (*Figure 2*), when considering only the FDK reconstruction (excluding O-8643 CBCTp), similar LCV values were calculated for the remaining systems.
- Spatial resolution (as defined by the modulation transfer function) and CT number linearity were comparable across the systems for similar acquisition modes.
- Geometric distortion for C-4030 and O-8643 (IGRT and CBCTp) was ~0.05mm, while this value was ~0.11mm and ~0.20mm for C-4343 and O-4343, respectively.
- Acquisition times were as short as 6s for O-8643, compared with ~16s for O-4343, 23-40s for C-4343, and ~33-60s for C-4030.

C-4343 System Characterization

- Numerous scans (n = 94) were acquired on C-4343 by varying the user-adjustable imaging parameters for the default *Head*, *Thorax*, *Pelvis*, and *Pelvis Large* acquisition modes.
  - For each scan, all other parameters remained unchanged.
- Variation of imaging energy from 80 kVp to 140 kVp (including 100 kVp and 125 kVp) generally resulted in improved LCV and reduced average NPS values (as energy increased).
- Similar trends were observed as the exposure (mAs) was increased for each default acquisition mode, though no noticeable trends were present for the uniformity, geometric distortion, and spatial resolution metrics as these parameters were varied.
- Variation in the image reconstruction algorithm produced similar results to those presented for the multi-system analysis.
- Application of the various convolution filters (*Smooth, Standard*, and *Sharp*) greatly impacted the measured NPS and spatial resolution metrics, with noise increased (*Figure 3*) and spatial resolution improved (*Figure 4*) for the *Sharp* filter when compared to the *Smooth* (and *Standard*) filter.
- When varying the applied noise suppression level (from *Very Low* to *Very High*, including *Low*, *Medium*, and *High* levels), average NPS values were reduced by a factor of ~2.5, while LCV was generally improved (*Figure 5*).
- Acquisition with increasing slice thicknesses varying from 1mm to 5mm (in increments of 1mm) demonstrated a slight reduction in NPS values.
- Increasing the radial FOV from ~48cm to 70cm for the *Pelvis* and *Pelvis Large* modes resulted in increased image noise, reduced spatial resolution, and improved uniformity metrics.

CONCLUSION

The O-8643 system, particularly in CBCTp mode, demonstrated modestly improved image quality overall relative to the other systems, including the novel C-4343 system. Contributing (at least partly) to this enhanced imaging capability is the faster gantry speed (up to 6 RPM for O-8643 compared to 1.5 RPM for C-4343) and larger imaging area. Similarly, the upgraded C-4343 system offered overall superior imaging capabilities compared to C-4030, representing a quantifiable improvement over the original platform, also (partly) attributable to the increased gantry speed (1.5 RPM for C-4343 compared to 1 RPM for C-4030) and larger detector panel. Additionally, variation of the user-adjustable imaging parameters on C-4343 offers the ability to optimize imaging performance according to the specific clinical needs of a given institution.

ACKNOWLEDGEMENTS

The authors extend their gratitude to Mu-Han Lin and Shanshan Tang of UTSW for their assistance in acquiring data for the O-4343 system.