Abstract Title

Blend+Proximity, a novel algorithm achieves high suppression of metallic streak artifacts and maximal preservation of contrast between soft tissues and iodinated contrast material on dual-energy CT scans

Background

Metallic implants significantly degrade CT images due to beam hardening, photon starvation and scatter artifacts. CT images acquired with low photon energies generally demonstrate superior contrast between soft tissues, better conspicuity of pathologies[2,5], and superior conspicuity of iodinated contrast[2,3,4], but are prone to significant degradation by artifacts arising from dense materials such as metallic implants. High-energy CT acquisitions demonstrate the reverse characteristics, with good suppression of metallic artifacts but relatively poor contrast. Using intermediate photon energy generally results in images that excel at neither artifact suppression nor optimal soft tissue contrast, but may produce a reasonable compromise between these factors. Several recent studies suggest that conspicuity of several pathologies depends on energy level, with neoplasms such as squamous cell carcinoma of the head and neck, pancreatic adenocarcinoma and hepatic lesions best visualized at around 40 keV[2,4,5].

Commercial software exists that can post-process dual-energy CT scans to reconstruct images which mimick CT acquisition at a single monochromatic energy level, and this energy level can be adjusted even after the scan is acquired. Although such adjustments can be useful and result in some improvement, this process can be time-consuming and the adjustments are generally limited to optimization of one of the features, while sacrificing the other, or producing a image that is a compromise between artifact suppression and conspicuity of iodinated contrast and soft tissues.

Case Presentation

Figure 1: Comparison of metallic artifacts, conspicuity of iodinated contrast, and visualization of soft tissues.

A novel algorithm "Blend+Proximity" was developed by the authors, with the specific aims of fully preserving the best qualities of the high- and low- energy CT images, without compromises that intermediate-energy images typically exhibit, and without optimizing one feature at the expense of the other. Blend+Proximity produces a single stack of CT image slices that demonstrate high suppression of metallic artifacts similar to that of high-energy images, and good visualization of soft tissues and iodinated contrast that is a hallmark of low-energy images (see Figure 1).

Cervical spinal CT myelographic images were acquired from a single patient with anterior metallic fusion hardware, following intrathecal iohexol injection. Scan was performed using a fast-kV switching dual-energy CT scanner at 80 and 140 kVp. Virtual mono-energetic images were reconstructed at 70-keV, 100-keV, and 130-keV.

Blend+Proximity algorithm was implemented using C++ and DCMTK. Each output voxel intensity (V) is a weighted average of the 2 corresponding voxels from the low-energy (e.g. 70-keV) and high-energy (e.g. 130-keV) virtual mono-energetic images, although poly-energetic images or different energy level values may also be used:

$$V_{output} = w \cdot V_{LowEnergy} + (1 - w) \cdot V_{HighEnergy}$$

The weighting factor (w, in the range 0 to 1, Figure 2) is calculated separately for each output voxel, and favors the low-energy input voxel due to the generally better soft tissue contrast on low energy images, unless the voxel is likely to be degraded by artifact, in which case the high-energy input voxel is favored. The likelihood and magnitude of artifact are considered to be higher (leading to decrease in w) if:

- Attenuation value is significantly lower within the lower-energy voxel (such as 70 keV) than within higher energy voxel (such as 130 keV), implying an area of dark streak artifact.
- The voxel is closer to other voxels on the same axial slice that represent metal or other very dense material (such as >1100 Hounsfield Units). The magnitude of this effect increases with the number of nearby voxels that represent metal, and decreases as 1 / distance-squared.
- In order to avoid sharp transitions between neighboring output pixels, which could theoretically produce undesired artifactual edges, a sigmoid curve is used to limit the value of weighting factor (w) between 0 and 1, and to ensure smooth transitions throughout the range of w (0 and 1).

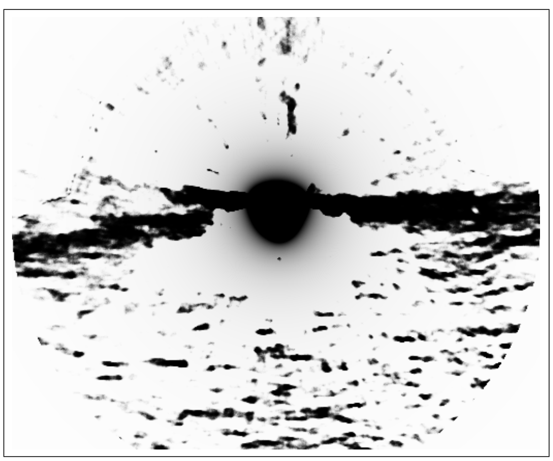

Figure 2: Voxel-by-voxel weighting factors, corresponding to images in figure 1. Black areas represent weighting factor (w) values close to 0 and thus favoring the high-energy pixels. White areas correspond to weighting factor value close to 1 and favoring the low-energy pixels. Weighting factors are calculated based on the proximity to metal, and based on the difference in pixel values between low energy and high energy images (significantly lower intensity on the low energy image voxel implies an area of streak artifact).

To objectively compare the image quality produced by this new algorithm against reconstructions at low, medium, and high energy levels, blind review and ranking of the images was performed by radiology attendings and trainees at 2 university hospitals at different time-points (N=24 and N=22). Results from both institutions were very similar, but the study conducted at the first institution did not include medium-energy images, and therefore only the second dataset is reported in this publication (N=22).

Identities of the reconstruction methods were concealed, and the reviewers were asked to rank the reconstruction methods based on the overall appearance of the produced images, with attention to:
- Conspicuity of intrathecal contrast material.
- Severity of metallic streak artifacts.
- Contrast of soft tissues and bone.

Statistical analysis was performed using LibreOffice Spreadsheet and R.

Outcome

Results of Survey (Condorcet Method)

- Condorcet voting method uses ranking of choices[6].
- The results are displayed as all permutations of 1-on-1 comparisons.
- Condorcet Method is generally more meaningful than pick-top-choice methods, especially in the presence of more than 2 choices or similar choices.

Comparison A vs. B	**Number of Raters Preferring A over B**	**Percentage of Raters Preferring A over B** with 95% Confidence Intervals		**P-value***	
Blend+Proximity vs. 100-keV	18 : 4	**81.8 %**	59.7 - 94.8	0.00434	**Significant**
Blend+Proximity vs. 130-keV	19 : 3	**86.4 %**	65.1 - 97.1	0.000855	**Significant**
Blend+Proximity vs. 70-keV	20 : 2	**90.9 %**	70.8 - 98.9	0.000121	**Significant**
100-keV vs. 130-keV	12 : 10	54.5 %	32.2 - 75.6	0.832	Not Significant
100-keV vs. 70-keV	20 : 2	90.9 %	70.8 - 98.9	0.000121	Significant
130-keV vs. 70-keV	12 : 10	54.5 %	32.2 - 75.6	0.832	Not Significant

* To reach the overall significance level of $P < 0.05$, the Šídák correction for 6 comparisons requires a threshold P-value of < 0.0085 for each of the tests. P value was obtained using the Binomial Test with 2-tailed distribution and Null-Hypothesis assuming proportion is not different from 50%.

Results of Survey (Top-Choice Method):

	Percentage of Reviewers Ranking each Algorithm as their **Top-Choice**	**Number of Reviewers** Ranking each Algorithm as their **Top-Choice**	**Iodine Conspicuity** Difference in Hounsfield Units between Thecal Sac and Muscle
Blend+Proximity	**68.2 %**	15	472
130-keV	13.6 %	3	148
100-keV	9.1 %	2	297
70-keV	9.1 %	2	444

Discussion

The reviewers preferred the new Blend+Proximity algorithm over the low, medium, and high energy virtual monochromatic images (significant $P < 0.0085$). Visual inspection of the CT image regions displaying iodinated contrast material and soft tissues suggest that Blend+Proximity achieves good visualization of these materials, similar to that of low-energy image, while suppressing the metallic streak artifact to a degree similar to the high-energy image. Measured differences in Hounsfield units between muscle and intrathecal iodinated contrast material also suggest that conspicuity of iodinated contrast is greatest on Blend+Proximity and low-energy image.

Blend+Proximity can potentially allow the reconstruction of a single image stack that has the best qualities of high and low energy images and which could be interpreted in a conventional manner, without the need for time-consuming adjustments of the virtual monochromatic energy level during interpretation that would otherwise be needed to realize the full benefits of dual-energy acquisition. This new algorithm can be considered to produce a single image set, wherein different voxels are reconstructed at differing energy levels, depending on the likelihood of artifact and proximity to metal. Although the weighing factor w was constrained to the range of 0 to 1 in this study, this can be extended outside of this range to extrapolate the voxel's virtual energy level beyond the low-energy or high-energy images.

Among the remaining reconstruction methods, medium-energy was the 2nd choice in the Condorcet analysis, followed by high-energy, and followed by low-energy. However, the differences were not statistically significant for the comparisons between 100-keV vs. 130-keV and 130-keV vs. 70-keV.

Conclusion

Most readers preferred the new Blend+Proximity reconstruction algorithm over a low energy (70 keV), medium (100 keV), and high energy (130 keV) CT images. This algorithm achieves high suppression of metallic artifacts while preserving contrast of soft tissues and good conspicuity of iodinated contrast. Additional investigation is desired, using images containing tumors or other pathologies, and also utilizing lower energy levels at approximately 40 keV, which has been previously suggested as optimal for visualization of various tumor types[2, 4, 5].

References

1. Yu L, Leng S, Mccollough CH. Dual-energy CT-based monochromatic imaging. AJR Am J Roentgenol. 2012;199(5 Suppl):S9-S15.
2. Bhosale P, Le O, Balachandran A, Fox P, Paulson E, Tamm E. Quantitative and Qualitative Comparison of Single-Source Dual-Energy Computed Tomography and 120-kVp Computed Tomography for the Assessment of Pancreatic Ductal Adenocarcinoma. J Comput Assist Tomogr. 2015 .
3. Meier A, Wurnig M, Desbiolles L, Leschka S, Frauenfelder T, Alkadhi H. Advanced virtual monoenergetic images: improving the contrast of dual-energy CT pulmonary angiography. Clin Radiol. 2015
4. Shuman WP, Green DE, Busey JM, et al. Dual-energy liver CT: effect of monochromatic imaging on lesion detection, conspicuity, and contrast-to-noise ratio of hypervascular lesions on late arterial phase. AJR Am J Roentgenol. 2014;203(3):601-6.
5. Lam S, Gupta R, Levental M, Yu E, Curtin HD, et al. Optimal Virtual Monochromatic Images for Evaluation of Normal Tissues and Head and Neck Cancer Using Dual-Energy CT. AJNR Am J Neuroradiol. 2015 Aug;36(8):1518-24.
6. Partha Dasgupta and Eric Maskin, The Fairest Vote of All. Scientific American March 2004.