PHYSICALLY MEANINGFUL VIRTUAL UNENHANCED IMAGE RECONSTRUCTION FROM DUAL-ENERGY CT

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ABSTRACT

Virtual unenhanced (VUE) image reconstruction techniques have the potential to eliminate the need for the acquisition of a non-contrast exam in imaging protocols that currently require both contrast and non-contrast computed tomographic (CT) scans. Here, we propose a new physically meaningful approach for the generation of VUE images as an application of a recently introduced technique for multi-material decomposition (MMD) from dual-energy CT. Rather than subtracting an estimate of the contribution to the image intensity in Hounsfield units due to contrast agent from the original image, the new algorithm replaces the estimated volume of contrast in each voxel by the same volume of the material that the contrast has displaced, namely, blood. Our results on both phantom and patient data demonstrate that VUE images can replace true unenhanced images effectively, thereby reducing radiation exposure and scan time of CT exams.

Index Terms— Virtual unenhanced, multi-material decomposition, computed tomography, fast kV switching, dual energy

1. INTRODUCTION

Computed tomography (CT) has been extensively used in assessing patients with suspected urinary stones [10], renal masses [3], and liver problems [4]. A common protocol for such CT examinations involves true unenhanced (TUE) image acquisition, typically followed by at least one more scan after the injection of an iodine-based contrast agent.

Dual-energy computed tomography (DECT) allows for the production of density images for a given material basis. Typical material basis are water and calcium or water and iodine. Assuming the later case, the density images correspond to the density map of water and the density map of iodine that yields the same projections as in the original DECT data [11]. These density maps can be used to produce monochromatic images, i.e., images equivalent to those obtained from a narrow-band, monochromatic X-ray beam [11]. It has been shown that

the adoption of DECT systems may allow for the elimination of the unenhanced scan of certain imaging protocols [10, 3]. This elimination can be achieved through the generation of virtual unenhanced (VUE) images [6], which are invariably described in the literature as some form of contrast or iodine subtraction based on a triple material decomposition method or simply the water image, converted to Hounsfield units, of the water/iodine pair [9, 2]. Significant reduction in radiation exposure (e.g. 35% in a study on the identification of renal masses [3]) and scan time as well as elimination of misregistration between two different acquisitions are the most important benefits of virtual unenhanced image reconstruction. The generation of high-quality VUE images, required to achieve such benefits, is the focus of this paper.

It is important to observe that the simple removal of contrast agent is not physically meaningful; instead, its replacement with the volume of blood that the contrast agent has displaced is the appropriate protocol. However, this protocol requires an accurate estimate of the blood volume displaced by the contrast agent. Recently, a novel multi-material decomposition technique based on DECT has been introduced [7]. In this technique the contribution of each constituent material in a mix of materials is expressed in terms of volume fractions, i.e., the percentage contribution in volume of each constituent

![Fig. 1: Monochromatic images in Hounsfield units at (a) 70 keV and (b) 140 keV.](image-url)
Fig. 2: Multi-material decomposition of the DECT data. The images shown in Fig. 1 have been decomposed into (a) fat, (b) blood, (c) bone, and (d) contrast agent components.

material of the mix. The method is based on a physico-
chemical model that assumes that materials in the body (as well as typical contrast agents) mix to form an ideal solution, in which the volume of a mixture is equal to the sum of the volume of its constituent parts [8].

In this work, we present a virtual unenhanced im-
age reconstruction technique which is based on multi-
material decomposition. We apply the method on both
phantom and anatomical data and provide qualitative
and quantitative evidence that TUE can be reliably re-
placed by VUE images.

2. BACKGROUND ON MATERIAL
DECOMPOSITION

We refer the reader to [1] for an exposition on the funda-
ments of dual-energy CT. Given a pair of monochromatic
images at two distinct energy levels (e.g, 70 keV and 140
keV, depicted in Fig. 1), as produced by some DECT
systems, the multi-material decomposition method in [7]
seeks an accurate estimation of volume fractions of
pre-selected materials for each voxel of the scanned vol-
ume. X-ray linear attenuation, denoted by $\mu_L$, is pri-
marily a function of incident X-ray energy $E$, the mass
density $\rho$, and composition of the material being imaged.
In [7] the mix of materials and contrast agents within the
human body is assumed to form an ideal solution. Un-
der this assumption it follows that the linear attenuation
coefficient $\mu_L$ can be expressed as:

$$\mu_L(E) = \sum_{i=1}^{N} \alpha_i \mu_{L,i}(E)$$

where $\alpha_i = \frac{v_i}{\sum v_j}$ is the volume fraction of material $i$ and $\sum_{i=1}^{N} \alpha_i = 1$. The goal of material decomposition
is to find $\alpha_i$’s under constrain that they sum up to 1. Mathematically, $N - 1$ measurements are needed to
decompose the solution into $N$ materials. Therefore, with
DECT measurements that provide only two equations,
simultaneous material decomposition into $N > 3$ mate-
rials is not well-posed. However, a sequential decompo-
tion into different triplets may still be possible, because
a poor choice of a material triplet may yield solutions
for $\alpha_i$ that violate the constraints $0 \leq \alpha_i \leq 1$, and this
violation can be used as a flag to indicate that another
choice of material triplet could be more appropriate for
a given location in the image [7]. Figure 2 shows the
decomposition of the images in Fig. 1 into its fat, blood,
bone, and contrast agent components.

3. VIRTUAL UNENHANCED IMAGING

The estimation of volume fractions described in [7] allows
for the development of a virtual unenhanced technique
that carries out a replacement rather than the removal
of contrast agent from the contrast-enhanced images.
Note that this operation does not have an elementary
counterpart for kVp-based dual-energy imaging, be-
cause of the non-linearity of the map between the two
representations [5].

The key piece of information necessary for the gener-
ation of virtual unenhanced images via the replacement
of contrast agent by blood is the volume of blood that
is displaced by the contrast. Under the same assump-
tion that the mix of blood and contrast agent form an
ideal solution used in [7], this volume must be equal to
that of the contrast agent. Having the volume fractions
of each material, we therefore simply replace the volume
of contrast agent by the same volume of blood. At a
given energy, we then reconstruct the linear attenuation
coefficient $\mu_{L,VUE}(E)$ of the unenhanced image as

$$\mu_{L,VUE}(E) = \sum_{i=1}^{N} \alpha_i \mu_{L,i}(E) + \alpha_1 \mu_{L,\text{contrast}}(E)$$

where the index $i_1$ refers to the contrast agent, and the
index $i_2$ refers to blood. Contrast subtraction, if still

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desired, can be obtained by omitting the second term in the sum on the right-hand side of (1). Furthermore, subtraction or replacement of any material for another, even if not a contrast agent, can be easily obtained through the appropriate change in (1).

As pointed out in the literature [3], an important limitation of current virtual unenhanced techniques based on triple material decomposition is that the material triplet is pre-selected and kept fixed throughout the analysis. A typical selection is fat, soft tissue, and iodine, which faces problems in image areas depicting a high concentration of calcium. The automated selection of material triplet in [7] overcomes this limitation without the separate post-processing step suggested in [3].

4. RESULTS AND DISCUSSIONS

Figure 3 shows a monochromatic DECT image of a phantom data taken at 70 keV, the estimated volume fractions for fat, calcium, iodine and the reconstructed VUE image. The two white rings in Fig. 3(a) contain a saline solution of 5% Visipaque, an iodine-based contrast agent. It is clear from 3(e) that the algorithm cancels the effect of the contrast agent without impacting other regions significantly. In particular, the calcium region indicated by one of the areas is much better preserved in the method here proposed. Quantitative results are shown in Fig. 4, which depicts boxplots of the signal intensity in the enhanced, virtual unenhanced, calcium, and saline-only regions. The boxplot clearly shows the ability of the algorithm to cancel the effect of the contrast agent while preserving the areas with calcium. Moreover, the concentration of Visipaque can be estimated from the volume fractions computed by the algorithm, yielding a value of 5.88%, a good approximation to the true value of 5%.

In an experiment with real patient data, two volume acquisitions were taken before and after injection of the contrast agent. Figure 2 shows a sample contrast-enhanced DECT image taken at 70 keV and its decomposition to fat, blood, bone, and contrast agent. Figures 5(a) and 5(b) show the reconstructed VUE and the true unenhanced images, respectively. A good qualitative agreement between the two images is observed. For quantitative comparison, five ROIs were selected as shown in Figure 5(b). Figure 5(c) compares the boxplots of the attenuation coefficient in these ROIs from the contrast enhanced (CE), reconstructed VUE, and true unenhanced images. The boxplots also demonstrate a good agreement between VUE and true unenhanced images (TUE), irrespective of the contrast agent density.

5. CONCLUSION

We proposed a novel approach for virtual unenhanced image construction, based on multi-material decomposition technique from dual-energy CT data. The algorithm

![Fig. 3: CT images of phantom containing different materials. (a) Monochromatic image at 70 keV; Volume fraction images for (b) fat, (c) calcium, (d) contrast agent and (e) reconstructed virtual unenhanced image. Note that the two white rings containing a mixture of 5% iodine in saline, are disappeared in the generated VUE image.](image)

![Fig. 4: Boxplot of data for contrast enhanced (CEN), virtual unenhanced(VUE), and true unenhanced (Saline) regions. In iodine regions both the water image of an water/iodine pair and the VUE image we propose have attenuation values in good agreement with those of a TUE image. However, calcium regions are appropriately left untouched by our algorithm, whereas the values of the water image are excessively low.](image)
replaces the estimated volume of contrast in each voxel by the same volume of the material that the contrast has displaced. We demonstrated the accuracy of the algorithm qualitatively and quantitatively on both phantom and anatomical data. Our results show that VUE images can replace true unenhanced images effectively, leading to reduction in both radiation exposure and scan time of CT exams and suggest a need for a change in current practices for the generation of VUE images.

References


