Enhanced Visualization of Pulmonary Perfusion in 4D Dual Energy CT Images

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Abstract— **Pulmonary embolism (PE) affects up to 600,000 patients and contributes to at least 100,000 deaths every year in the United States alone. Diagnosis of PE can be difficult as most symptoms are unspecific. Computed Tomography (CT) angiography is the reference for diagnosing PE. CT angiography produces grayscale images with darker areas representing any mass filling defects, making the analysis of the images difficult. This article demonstrates a method using the combination of energy levels in Dual Energy CT images to highlight the presence of PE in the lung. The results show that pairing different energy levels from 40 to 140 keV can increase the contrast between well perfused areas and underperfused areas of the lung. In addition, the visualization used in the current study complies with the window/level settings usually employed by radiologists.**

I. INTRODUCTION

Acute pulmonary embolism (PE) is a common condition that consists of the obstruction of one or more arteries in the lungs as a complication of deep vein thrombosis. Studies have shown that acute pulmonary embolism mortality rates can reach 75% during initial hospital admission [1] and after the hospital discharge 30% within 3 years [2]. Although it can be successfully treated with anticoagulants, delays in diagnosis have shown to increase the risk of death [3]. There is evidence that 3D texture features correlate with ventilation and vascularization of the lung parenchyma [4], [5] and that pulmonary embolism induces wedge–shaped pleura–based regions of heterogeneous increased attenuation in unenhanced computed tomography (CT) scans that are also visible on contrast–enhanced CT [6]. Dual Energy Computed Tomography (DECT) produces four dimensional (4D) data in a single scan. In addition to the three spatial coordinates (x,y,z) images are sampled at the level of x–ray energy for image acquisition (80 and 140 keV, hence the name dual energy). DECT images are difficult to visualize as radiologists can either browse through the 3D volume showing single slices or modify the energy level for a single slice but not the two at the same time. DECT imaging exploits the fact that different materials present different energy–attenuation curves. Specifically, iodine components present in contrast agents have a much faster decay in the energy–attenuation curve than water. Several studies have explored the idea of visualizing and assessing the pulmonary perfusion in acute pulmonary embolism cases using the Dual Energy CT protocol recommended by Siemens Healthcare (manufacturer of Somatom Definition scanner) [7], [8], [9]. These studies use linear combinations of the two source energy levels (80 and 140) as suggested by [10] for generating iodine distribution maps in the lung parenchyma. In this paper we apply a similar approach that validates these findings on data generated with a different Dual Energy protocol using a GE Healthcare Gemstone Spectral Imaging (GSI) scanner. The main feature of the GSI scanner is that it obtains a larger amount of information from a single acquisition and provides 3D volumes sampled at 40 to 140 keV in steps of 10 keV. First, we explore the optimal combination of energy levels, which highlights the difference between EP cases and control cases. Finally, this combination is used for visualizing the CT images adding color coded information, which is in accordance to the window and level settings known by radiologists.

The rest of the paper is organized as follows: Section II explains the methods and materials used, defining the experimental setup for choosing the best pair of energy levels and how they can be integrated into a vector image visualization tool as a false color layer. Section III contains the main results of the work, which are discussed in Section IV and conclusions and future work are described in Section V.

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II. MATERIALS AND METHODS

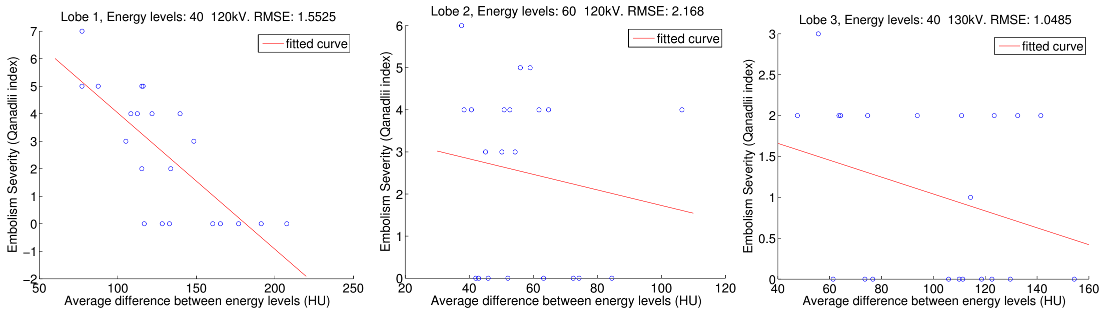
A. Dataset

Pulmonary parenchyma ischemia in 4D dual energy CT (DECT) images of 25 patients were identified in collaboration with the emergency radiology of the University Hospitals of Geneva. The images in the dataset contain approximately 300 slices per patient and energy level. Energy levels are sampled from 40 to 140 keV in steps of 10 keV. The image resolution is approximately isotropic in the spatial coordinates, with horizontal resolution of $0.83mm/voxel$ and vertical resolution of $1mm/voxel$.

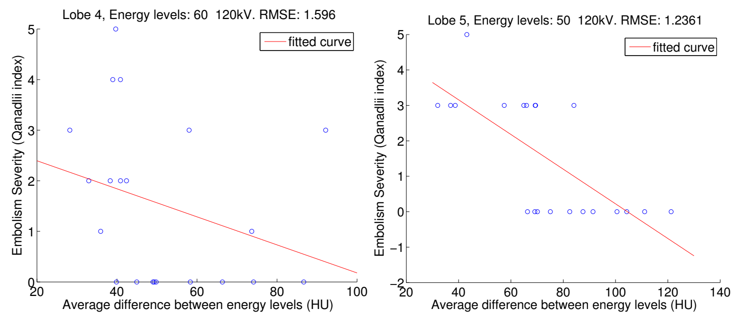
For each patient, the five pulmonary lobes were manually segmented and the Qanadli index (Q) [11] was manually computed as a measure of the obstruction on a lobe basis. The Qanadli index is calculated by adding a score per artery in the lobe: 0 if there is no obstruction, 1 if there is partial obstruction and 2 if the artery is completely obstructed.

B. Combination of energy levels

According to the dual energy protocol and reconstructed images, iodine components have a larger attenuation value



(a) Regression model for the lower right lobe. (b) Regression model for the lower left lobe. (c) Regression model for the middle right lobe.



(d) Regression model for the upper left lobe. (e) Regression model for the upper right lobe.

Fig. 1: Average value of the difference image between the optimal pair of energy levels against the Qanadli index for each lung lobe showing that the slope is always negative.

	Lower right	Lower left	Middle right	Upper left	Upper right
$I_{40} - I_{120}$	**1.5525**	2.1685	1.0486	1.5978	1.2370
$I_{40} - I_{130}$	1.5527	2.1685	**1.0485**	1.5977	1.2370
$I_{40} - I_{140}$	1.5527	2.1685	**1.0485**	1.5977	1.2370
$I_{50} - I_{120}$	1.5652	2.1683	1.0497	1.5970	**1.2361**
$I_{50} - I_{130}$	1.5651	2.1683	1.0496	1.5970	**1.2361**
$I_{50} - I_{140}$	1.5648	2.1683	1.0495	1.5969	**1.2361**
$I_{60} - I_{120}$	1.5899	**2.1680**	1.0533	**1.5960**	1.2375
$I_{60} - I_{130}$	1.6523	2.1824	1.0576	1.6020	1.2497
$I_{60} - I_{140}$	1.6509	2.1824	1.0573	1.6019	1.2494

TABLE I: Root mean squared error of model fit for each lobe and each pair of high and low energy levels considered.

for low energy levels than for higher energy levels, whereas other materials such as water have a similar attenuation for all energy levels. Therefore, the presence of contrast agent (which is rich in iodine) can be found by analyzing the attenuation difference between low energy levels and high energy levels. We thus assume that the higher the QI, the lower the difference between high and low energy levels.

Based on this assumption we obtained the difference images between pairs of energy levels, and computed the average values for healthy and PE cases. This computation was performed on a single lobe basis, since each lobe has a specific vascularization pattern.

C. Visualization

Human vision has strong limitations analyzing grayscale images (from 50 to 150 gray scales can be separated depending on the articles [12]). Studies have also shown that the human vision successfully exploits color information, distinguishing thousands of colors [13]. It is therefore tempting to use mainly color information to display complex data. Radiologists are well trained to distinguish differences in luminance and intensity, since it is easy to associate variation of a physical magnitude (e.g.: density, attenuation, etc.) to variations of light intensity. On the other hand, color information is by definition three–dimensional (2D if only hue and saturation are considered) which is impossible to sort with respect to a physical magnitude. Computer screens are based on the RGB (red, green, blue) color space. In order to present anatomical information as well as perfusion information in the same image, we decided not to change the anatomical information from the grayscale space and use color variations for perfusion. With this idea in mind, we used the following scheme for each of the RGB channels:

$$R = I_{standard} + K_R(I_{low} - I_{high}), \quad (1)$$
$$G = I_{standard} + K_G(I_{low} - I_{high}), \quad (2)$$
$$B = I_{standard}, \quad (3)$$

where I_{high}, I_{low} are the images acquired at one of the three highest (120, 130 and 140 keV) or three lowest energy levels (40, 50 and 60 keV). $I_{standard}$ is the image acquired at 70 keV. K_R and K_G are parameters to be determined.

In order to satisfy relative luminance invariance further restrictions were applied: first, the definition of relative luminance Y according to the RGB components [14] and second, that the relative luminance remains equal to the standard CT image (70keV):

$$Y = 0.2126R + 0.7152G + 0.0722B, \quad (4)$$
$$Y = I_{standard}. \quad (5)$$

which translates into a fixed ratio for K_R and K_G:

$$K_R = -\frac{0.7152}{0.2126} K_G. \quad (6)$$

This produces a grayscale image where large differences in perfusion are color–coded. Well perfused tissues have relatively higher values of green and blue channels, which translates into a cyan tone. Uncolored areas ($I_{low} - I_{high} \approx 0$) or red areas ($I_{low} - I_{high} < 0$) reflect the absence of iodine components, and therefore low perfusion.

The grayscale images respect the Hounsfield scale of standard energy level used in single energy CT, and therefore radiologists can still use window/level settings for visualization.

III. RESULTS

For each pair of energy levels studied, linear regression of the relation between the Qanadli index and the average values in the difference image was computed. Figure 1 illustrates this analysis. In all cases there is an inverse relation between the average difference measured in Hounsfield units and the severity of the embolism.

Table I shows the root mean squared error (RMSE) value of a linear fit of the model $\tilde{Q} = a + b\overline{(I_{low} - I_{high})}$.

Since the relations observed between the Qanadli index and the average value of the difference images are not enough for discriminating healthy lobes from embolism, visual interpretation and/or further computer analysis are still required for this task. Figures 2 and 3 show the visual appearance when low and high energy levels are chosen for RGB channels as explained in section II-C, where the distribution of contrast agent is represented with cyan tones. Inhomogeneities in the distribution of contrast agent (uncoloured and red areas) are much more visible in the EP cases than in healthy lobes.

Results supports the findings of Thieme et al. [7], [8], [9] on Siemens dual energy scanners that use a very different technique from the GE dual energy scanners used in our study and extend them to a broader set of energy levels, which are chosen based on a simple linear regression model.

IV. DISCUSSIONS

Our current study is different from previous studies attempting to use DECT for embolism detection [7], [8], [9] in the scanner technology used and the methods we applied to visualize the images. In this study we used a GE Healthcare GSI scanner able to provide 3D volumes sampled at 40 to 140 keV in steps of 10 keV whereas all previous studies used a Siemens scanner. The GE Healthcare scanner permits to choose any energy level, which allows showing the largest contrast between well perfused areas and underperfused areas of the lung. Table I shows that the pairs that correlate better with a linear model are not consistent among the various lobes (lower right, lower left, middle right, upper left and upper right) which is a consequence of the variations in the vascularization among lobes. It also demonstrates the need of multiple energy levels to improve PE diagnosis: since there is no optimal combination of energy levels for all lobes, it will be beneficial for the clinicians to have access to various energy levels at the moment of visualizing the images. Similarly to the preset window and level values, interfaces designed for DECT data should integrate presets for combining various energy levels. Noise can also vary in the energy levels and unfortunately the denoising techniques of the various producers or even the raw data are usually not available on DECT, which could otherwise be used for selecting the optimal parameters.

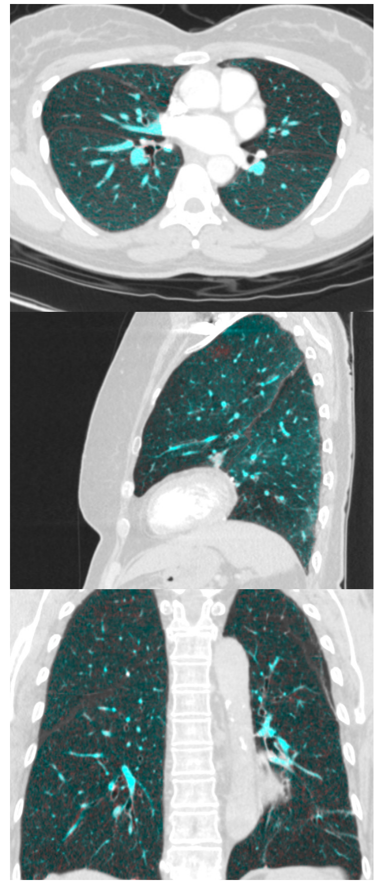


Fig. 2: Control cases present homogeneously blue–colored parenchyma, since there is a large presence of contrast components. The images are set in the lung window (-1200, 200 HU) and a mask was applied to show color information only in the lung region.

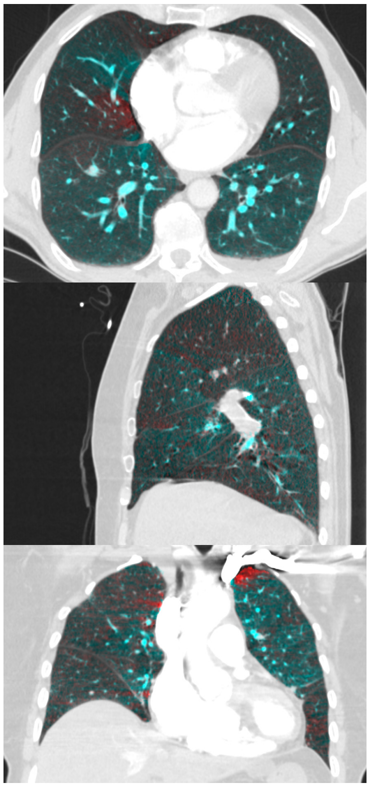


Fig. 3: EP cases highlight differences in perfusion with strong contrast between light blue areas and red or uncolored areas. The images are set in the lung window (-1200, 200 HU) and a mask was applied to show color information only in the lung region.

V. CONCLUSION

In this paper a visualization of 4D DECT stacks is proposed for the diagnosis of pulmonary embolism to better analyze perfusion in the various lung lobes. The method presented studies first the optimal energy levels for highlighting the inhomogeneities in lung perfusion and then combines them into a 3D vector image that complies with the usual window/level settings employed by radiologists. Although the visualization is improved, subtle differences in perfusion are hard to observe and further computer–based analysis might still be required. Particularly a quantitative measure of perfusion per lobe is currently being studies that could help radiologists to take decisions quickly. Future work includes combining the visualization of perfusion maps with texture–based features that have shown to be useful in acute PE diagnosis [15], [5], [16].

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REFERENCES

[1] Samuel Z Goldhaber, Luigi Visani, and Marisa De Rosa, "Acute pulmonary embolism: clinical outcomes in the international cooperative pulmonary embolism registry (icoper)," *The Lancet*, vol. 353, no. 9162, pp. 1386 – 1389, 1999.

[2] Jr Anderson, Frederick A., H. Brownell Wheeler, Robert J. Goldberg, David W. Hosmer, Nilima A. Patwardhan, Borko Jovanovic, Ann Forcier, and James E. Dalen, "A population-based perspective of the hospital incidence and case-fatality rates of deep vein thrombosis and pulmonary embolism: The worcester dvt study," *Archives of Internal Medicine*, vol. 151, no. 5, pp. 933–938, 1991.

[3] Savas Ozsu, Funda Oztuna, Yilmaz Bulbul, Murat Topbas, Tevfik Ozlu, Polat Kosucu, and Asiye Ozsu, "The role of risk factors in delayed diagnosis of pulmonary embolism," *The American Journal of Emergency Medicine*, vol. 29, no. 1, pp. 26 – 32, 2011.

[4] Balaji Ganeshan, Kenneth A. Miles, Rupert C. D. Young, and Chris R. Chatwin, "Three–dimensional selective–scale texture analysis of computed tomography pulmonary angiograms," *Investigative Radiology*, vol. 43, no. 6, pp. 382–394, June 2008.

[5] Antonio Foncubierta-Rodríguez, Pierre-Alexandre Poletti, Alexandra Platon, Alejandro Vargas, Henning Müller, and Adrien Depeursinge, "Texture quantification in 4D dual energy CT for pulmonary embolism diagnosis," in *MICCAI workshop MCBR–CDS 2012*, 2013, vol. 7723 of *Springer LNCS*, pp. 45–56.

[6] Heidi C. Schwickert, Franz Schweden, Hans H. Schild, Rolf Piepenburg, Christoph Düber, Hans-Ulrich Kauczor, Christian Renner, Stein Iversen, and Manfred Thelen, "Pulmonary arteries and lung parenchyma in chronic pulmonary embolism: preoperative and postoperative CT findings.," *Radiology*, vol. 191, no. 2, pp. 351–357, 1994.

[7] Sven F. Thieme, Thorsten R. C. Johnson, Christopher Lee, Justin McWilliams, Christoph R. Becker, Maximilian F. Reiser, and Konstantin Nikolaou, "Dual–energy CT for the assessment of contrast material distribution in the pulmonary parenchyma," *American Journal of Roentgenology*, vol. 193, no. 1, pp. 144–149, 2009.

[8] Sven F. Thieme, Christoph R. Becker, Marcus Hacker, Konstantin Nikolaou, Maximilian F. Reiser, and Thorsten R. C. Johnson, "Dual energy CT for the assessment of lung perfusion—correlation to scintigraphy," *European Journal of Radiology*, vol. 68, no. 3, pp. 369–374, 2008.

[9] Eun Jin Chae, Joon Beom Seo, Yu Mi Jang, Bernhard Krauß, Choong Wook Lee, Hyun Ju Lee, and Koun-Sik Song, "Dual–energy CT for assessment of the severity of acute pulmonary embolism: Pulmonary perfusion defect score compared with CT angiographic obstruction score and right ventricular/left ventricular diameter ratio," *American Journal of Roentgenology*, vol. 194, no. 3, pp. 604–610, 2010.

[10] Thorsten R. C. Johnson, Bernhard Krauß, Martin Sedlmair, Michael Grasruck, Herbert Bruder, Dominik Morhard, Christian Fink, Sabine Weckbach, Miriam Lenhard, Bernhard Schmidt, Thomas Flohr, Maximilian F. Reiser, and Christoph R. Becker, "Material differentiation by dual energy CT: initial experience," *European Radiology*, vol. 17, no. 6, pp. 1510–1517, June 2007.

[11] Salah D. Qanadli, Mostafa El Hajjam, Antoine Vieillard-Baron, Thierry Joseph, Benoit Mesurolle, Vincent L. Oliva, Olivier Barré, Frédéric Bruckert, Olivier Dubourg, and Pascal Lacombe, "New CT index to quantify arterial obstruction in pulmonary embolism," *American Journal of Roentgenology*, vol. 176, no. 6, pp. 1415–1420, 2001.

[12] Fred Attneave, "Some informational aspects of visual perception.," *Psychological Review*, vol. 61, no. 3, pp. 183–193, May 1954.

[13] Rangaraj M Rangayyan, Begoña Acha, and Carmen Serrano, *Color image processing with biomedical applications*, SPIE Press Bellingham, 2011.

[14] Michael Stokes, Matthew Anderson, Srinivasan Chandrasekar, and Ricardo Motta, "Standard default color space for the Internet," Tech. Rep., World Wide Web Consortium, 1996.

[15] Antonio Foncubierta-Rodríguez, Oscar Alfonso Jiménez del Toro, Alexandra Platon, Pierre-Alexandre Poletti, Henning Müller, and Adrien Depeursinge, "Benefits of texture analysis of dual energy CT for computer–aided pulmonary embolism detection," in *The 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Conference (EMBC 2013)*, 2013.

[16] Adrien Depeursinge, Antonio Foncubierta-Rodríguez, Alejandro Vargas, Dimitri Van De Ville, Alexandra Platon, Pierre-Alexandre Poletti, and Henning Müller, "Rotation–covariant texture analysis of 4D dual–energy CT as an indicator of local pulmonary perfusion," in *IEEE 10th International Symposium on Biomedical Imaging*. Apr. 2013, ISBI 2013, pp. 149–152, IEEE.