Contrast agent free regional ventilation imaging in CT and MRI

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Background

High-resolution medical imaging data, such as computed tomography (CT) and magnetic resonance imaging (MRI) scans, often contain complex local variations that are difficult to capture using global statistics. In obstructive diseases, such as asthma, and COPD, regional tissue heterogeneity plays a key role, and there's a need for methods that can quantify localised variations in order to identify and assess disease.

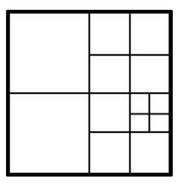
The first part of this project focuses on applying 2D and 3D image decomposition to MRI images to identify regions of homogeneity and heterogeneity. Various differentiation measures will be used to compare octree (2D Slice-wise) and quadtree (3D) decomposition.
The second half overviews the differentiation between clinical CT image filtering kernels in restrictive lung diseases, as assessing image kernel selection's impact on the resulting CT image quality is important to understand the sequential effect on image-derived quantitative measurements, such as CT-derived ventilation [2]. Furthermore, these methods are applied to the specific gas volume [2] to find the difference between the kernels and the diseases. CT images are used to generate an analysis based on the characteristics of four different reconstruction filters.

Part A: MRI Image

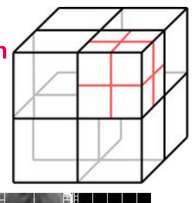
Quadtree Decomposition

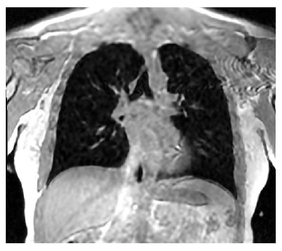
An algorithm splitting 2D space into four square regions. It maintains if it is homogeneous, if not, split the squares into smaller area. Consequently, the image can visually distinguish between homogeneous or heterogeneous areas.The **quadtree** is performed in slices of each image datasets in **2D observation**. On the other hand, the **Octree Decomposition** is an enhanced version, performing in **3D voxel** level for each slices.

Quadtree Decomposition



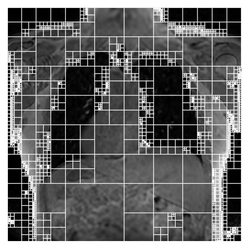
Octree Decomposition



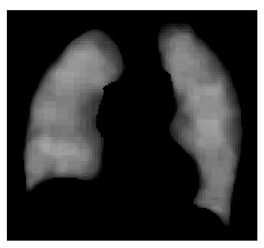


1 Original Lung Image

2 Segmenting the lung area.



3 An image after applying Quadtree decomposition at 20 percent.



4 An image after applying segmented mask and quadtree decomposition.

5 Quadtree mask: It demonstrates the homogeneity and heterogeneity of the regions detected in the image based on the image's intensity.

Heterogeneity

Boxes / Area of Lung (pixel)

The created boxes represent the intensity values detected in an image. Consequently, aggregating the contrast of the boxes within the lung area results the heterogeneity of the MRI image.

While octree decomposition was implemented by the supervisor, Part A mainly focuses on performing quadtree decomposition on a MRI image and comparing it with octree decomposition.

Three matrices, pearson correlation, MSE, and MAE, were used to contrast the two decompositions. Furthermore, the heterogeneity values obtained from both algorithms were compared to analyse the performance of each decomposition.

Part B: CT Image

Steps

Specific Gas Volume

The **specific gas volume** (SVg) [2] quantifies the ratio of air to tissue within each CT image voxel, providing a physiological measure of lung ventilation.
In this project, SVg is used to analyse the four reconstruction kernels, **B30f, B35f, B60f, and B70f.**

Comparing Kernels

Voxel-level Pearson correlation was used to assess the impact of the four reconstruction kernels: B30f with the greatest filtering, B35f, B60f, and B70f with the least filtering, on measured CT image intensity (Hounsfield unit HU).
This approach enables the identification of kernels preserving the same underlying ventilation information or diverge due to their frequency characteristics.
These comparisons further allow for the evaluation of disease impact across kernels. Furthermore, the correlation measures facilitate disease comparisons, offering insights into which reconstruction kernels may demonstrate greater sensitivity or robustness for disease characterisation.

Comparing Diseases

The specific gas volume can be used to demonstrate the differences between the three lung conditions.

Common Comparison Matrix

Pearson Correlation

This matrix is employed as the primary comparison approach in this research. It provides a robust, scale-independent, and interpretable measure of similarity in intensity patterns across image files. Furthermore, the correlation is computed at the voxel level, which is essential for analysing medical imaging modalities such as CT and MRI, where voxel level relationships carry direct physiological significance.

Results: Part A

QtD and OtD Value:

OTD: 30.348534 **QTD:** 0.283689

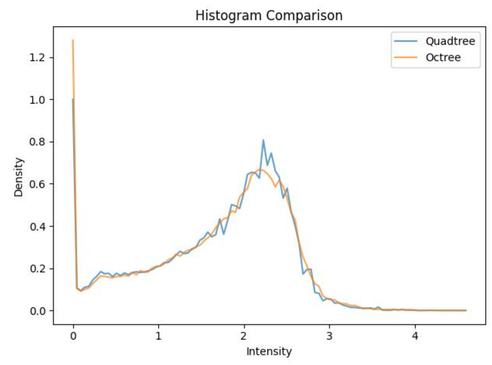
The large difference between the OTD and QTD values arises because OTD is performed in 3D, while QTD is based on 2D. The higher dimensionality and scale of OTD naturally produce larger values.

Comparison Matrices:

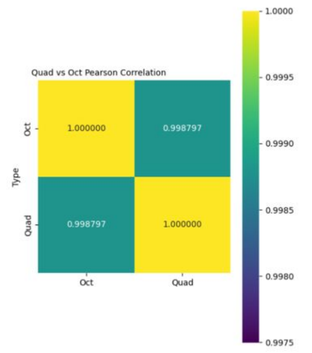
Applied Contrast Matrices:
MAE: 0.0938507691025734| MSE: 0.0212196484208107 | Pearson: 0.9840791821479797

MAE and MSE values close to 0 indicates that the two compared features are similar.
Pearson correlation close to 1 demonstrates a strong similarity between the compared features.

Intensity Histogram Similarity:



The diagram illustrates the performance quality of both quadtree and octree decompositions. The quadtree produces sharper intensity detection due to its 2D environment. In contrast, the octree yields a smoother histogram because it operates in 3D, allowing features to be detected across more dimensions, whereas the quadtree can only divide a square into four parts.

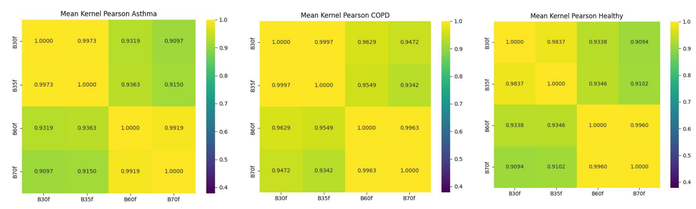


The heatmap represents the similarity between the octree and quadtree decomposition by using Pearson correlation.

The following results indicate that the octree and quadtree decompositions are similar, based on the contrast matrix results.
On the other hand, the octree performs better in generating detailed intensity detection that the quadtree.

Results: Part B

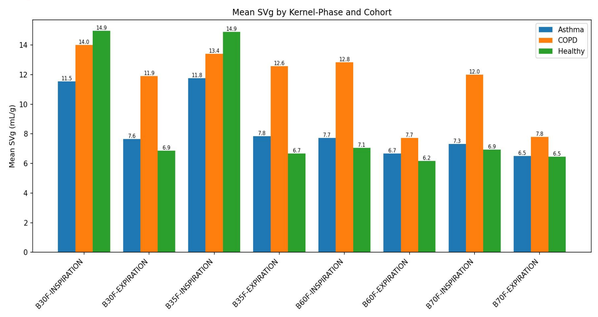
Mean Pearson Correlation for four kernels



Two groups were identified after generating Pearson correlation results from the entire patient dataset.

Group A : Higher filtering (B30f and B35f)
These kernels are characterised by a higher degree of filtering, as indicated by their lower frequency values. This stronger filtering smooths the image by removing high-frequency noise. According to the heatmap, the **B30f** kernel applies the greatest filtering among the four, and its strong correlation with the **B35f** kernel places them in the same group.
Group B : Low Filtering Group (B60f and B70f)
This results in sharper images that preserve fine details, though they may appear noisier. Sharper kernels may make features more visible to the human eye, but they also detect excessive detail, leading to contrasting results with Group A.
Lastly, the consistency of the three heatmaps demonstrates that this distinction between the two groups of kernels remains true regardless of specific lung conditions.

Specific Gas Volume



Reconstruction Kernel Effects on SVg patterns
Group A: Suppress noise while highlighting global density shits, producing the largest SVg contrast in healthy lungs.
Group B: Enhance edges and local heterogeneity but flatten intensity, reducing SVg contrast and shifting healthy values closer to disease.
Disease patterns:
COPD shows high expiratory SVg across kernels due to robust heterogeneity and air trapping. **Asthma** remains intermediate, reflecting milder, reversible changes. **Healthy** showed the highest SVg in the group A.
However, values decreased with sharper kernels due to less edge detection compared to disease lungs.
Clinical implications:
Kernel choice determines whether SVg reflects global ventilation (smooth) or local structure (sharp). Thresholds must be kernel-specific or harmonised, with sharp kernels particularly useful for COPD detection.

Conclusion

The QTD and OTD produced similar outputs, as confirmed by three different contrast matrices. However, OTD histogram indicated that octree decomposition generated more detailed results compared to quadtree decomposition.

The kernels are divided into two groups: B30f and B35f, and B60f and B70f.
B30f and B35f produced similar results and generated higher SVg values compared to the other two reconstruction kernels.

Reference

[1] Subramaniam, K., et al. "Quantifying tissue heterogeneity using Quadtree decomposition." *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Aug. 2012, pp. 4079–4082, https://doi.org/10.1109/embc.2012.6346863.

[2] Salito, Caterina, et al. "Influence of CT reconstruction settings on extremely low attenuation values for specific gas volume calculation in severe emphysema." *Academic Radiology*, vol. 18, no. 10, Oct. 2011, pp. 1277–1284, https://doi.org/10.1016/j.acra.2011.04.019.

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