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Quantifying recovery coefficients for partial volume effect correction in pet/ct: an anthropomorphic phantom approach

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Abstract: The partial volume effect (PVE) in positron emission tomography/computed tomography (PET/CT) imaging leads to inaccurate quantification of radiotracer uptake, particularly in small structures or regions with low activity. This study proposes a method for calculating recovery coefficients (RCs) to correct for the PVE in PET/CT images using a customized anthropomorphic body phantom. The phantom was designed to replicate human body anatomy, including various organs and tissues, with controlled activity distributions. PET/CT scans were acquired at different spatial resolutions, and the RCs were derived by comparing the measured and true activity concentrations. Our findings demonstrate that the RCs vary based on the size and shape of the region of interest (ROI) and the resolution of the PET scan. These recovery coefficients can be applied to improve quantitative accuracy in PET/CT imaging, particularly for small lesions and organs. The results highlight the effectiveness of using a customized anthropomorphic phantom for PVE correction and the potential clinical benefits of this method in diagnostic imaging.

Keywords: PET/CT Imaging, Partial Volume Effect (PVE), Recovery Coefficients (RCs), Image Quantification, Anthropomorphic Phantom, Phantom Studies in Imaging, Resolution Recovery, PET Image Correction, Quantitative PET Imaging.

Introduction: Positron emission tomography (PET) combined with computed tomography (CT) is a powerful non-invasive imaging modality widely used for

diagnosing and staging various cancers, assessing cardiac conditions, and monitoring treatment response. PET provides functional information on metabolic activity, while CT offers anatomical details, making PET/CT a gold standard for many clinical applications. However, one of the challenges in PET imaging is the partial volume effect (PVE), which occurs when the spatial resolution of the PET scanner is insufficient to accurately delineate small structures, resulting in an underestimation of radiotracer uptake in smaller regions.

The PVE arises from the finite resolution of PET scanners, which leads to a smearing of activity from the true region of interest (ROI) into adjacent areas. This effect can be particularly problematic when quantifying small tumors, lymph nodes, or other organs with low tracer uptake. As a result, PET images may underestimate the metabolic activity of small lesions, leading to inaccurate diagnostic conclusions. To address this issue, recovery coefficients (RCs) are often calculated to correct for the PVE. These coefficients are used to adjust the measured activity concentrations, providing more accurate representations of the true tracer uptake.

Typically, RCs are derived empirically by simulating or measuring the response of a scanner to objects of various sizes and activity distributions. In this study, we aim to calculate the RCs for PVE correction using a customized anthropomorphic body phantom. This phantom is designed to mimic the anatomical structure of the human body, including organs and tissues of varying sizes and shapes. By performing PET/CT scans on this phantom, we can measure the impact of PVE and calculate the appropriate RCs for different regions of interest, improving the accuracy of quantitative PET imaging.

METHODS

Phantom Design and Construction:

A customized anthropomorphic body phantom was designed to replicate human body anatomy. The phantom includes a torso, brain, liver, heart, lungs, kidneys, and other smaller organs, with embedded spherical lesions of varying sizes to simulate tumors. The phantom was constructed using materials that approximate the tissue characteristics of human organs, including densities and attenuation properties. The activity distribution within the phantom was controlled, with the option to set different levels of radiotracer uptake in various regions to simulate physiological and pathological conditions.

PET/CT Imaging Protocol:

PET/CT scans were performed using a state-of-the-art PET/CT scanner. The phantom was filled with a uniform concentration of F-18 fluorodeoxyglucose (FDG), a commonly used radiotracer, and scanned at different resolutions. Scans were acquired at multiple slice thicknesses, ranging from 2.5 to 10 mm, to evaluate the effects of spatial resolution on the PVE. For each scan, the PET images were co-registered with the corresponding CT images to obtain anatomical information.

Calculation of Recovery Coefficients:

Recovery coefficients were calculated by comparing the measured activity concentration in a region of interest (ROI) to the true activity concentration within the phantom. The true activity concentration was known because it was manually defined during the phantom design process. The recovery coefficient for each ROI was determined as:

Statistical Analysis:

Statistical analysis was conducted to evaluate the variability of recovery coefficients across different ROIs and scan resolutions. The standard deviation (SD) of RCs for each ROI was calculated to assess the reproducibility of the results. Linear regression analysis was used to assess the relationship between lesion size and RCs, as well as the effect of spatial resolution on the PVE.

RESULTS

Recovery Coefficients for Different Organs and Lesions:

The recovery coefficients varied significantly across different regions of interest. Small lesions, particularly those with diameters less than 2 cm, exhibited lower recovery coefficients, with an average value of 0.6-0.8, indicating a significant underestimation of activity in these regions due to the PVE. Larger organs, such as the liver and lungs, had recovery coefficients closer to 1.0, indicating that their activity concentration was measured with relatively high accuracy.

Effect of Spatial Resolution on Recovery Coefficients:

The resolution of the PET scan had a pronounced effect on the recovery coefficients. As the slice thickness decreased (improving spatial resolution), the RCs for small lesions increased, with an improvement of approximately 10-15% at the highest resolution. This indicates that high-resolution scans help to mitigate the PVE, especially for small structures.

Statistical Analysis and Variability:

The standard deviation of RCs across different ROIs was found to be lower for larger organs, reflecting more consistent measurements. For smaller lesions, however, the standard deviation was higher, indicating greater variability in the PVE correction for these regions. Regression analysis revealed a significant inverse

relationship between lesion size and RC, with smaller lesions showing progressively lower recovery coefficients.

Recovery Coefficients for Different Organs and Lesions:

The calculated recovery coefficients (RCs) varied considerably depending on the size and type of the region of interest (ROI). Small lesions, especially those with diameters less than 2 cm, displayed significantly lower recovery coefficients due to the partial volume effect (PVE). In particular, lesions with diameters of 1–2 cm had an average RC ranging from 0.6 to 0.8, indicating a substantial underestimation of activity in these areas. For example, a spherical lesion with a diameter of 1.5 cm located in the liver showed a measured activity concentration of 3.5 kBq/ml, whereas the true activity concentration was 5.5 kBq/ml, resulting in an RC of 0.64. This underestimation is attributed to the inability of the PET scanner to resolve the small lesion at its native resolution, leading to activity spilling into surrounding tissues.

On the other hand, larger organs, such as the liver, kidneys, and lungs, displayed RCs closer to 1.0, reflecting a more accurate representation of the true activity concentration. For example, in the liver (a large organ), the measured activity concentration was 5.4 kBq/ml, and the true concentration was also 5.5 kBq/ml, yielding an RC of 0.98, which indicates minimal impact from the PVE.

Interestingly, the heart, which is also a large organ, showed an RC of 0.95, suggesting that even for organs with significant activity, the PVE does still slightly affect the quantification, especially in regions close to the boundaries of the heart or in areas where the myocardium transitions to adjacent tissues, such as fat.

Effect of Spatial Resolution on Recovery Coefficients:

A key finding of this study is that the spatial resolution of PET imaging plays a significant role in the extent of the partial volume effect. As spatial resolution improved (i.e., when slice thickness decreased), the recovery coefficients for small lesions increased. For instance, at the highest resolution (2.5 mm slice thickness), a 2 cm lesion in the phantom showed a significant improvement in RC, with an RC of 0.80, compared to 0.65 at a lower resolution (10 mm slice thickness). This improvement in RC is due to the ability of higher-resolution scans to better delineate small structures, reducing the smearing of activity from surrounding regions.

To further illustrate, consider a spherical lesion with a diameter of 3 cm, located in the lungs. When scanned at the 10 mm slice thickness, the lesion exhibited a recovery coefficient of 0.75. However, when scanned at 2.5 mm resolution, the RC improved to 0.89, reflecting a better ability of the PET scanner to resolve the lesion and its boundaries more accurately. This suggests that high-resolution scans, which are capable of more accurately reconstructing fine details, are critical for improving the quantification of small lesions.

For larger regions, the effect of spatial resolution on RCs was less pronounced. For example, the liver, which had a true activity concentration of 5.5 kBq/ml, yielded an RC of 0.98 at both low and high resolutions, confirming that large organs are less affected by the PVE compared to small lesions.

Statistical Analysis and Variability:

The standard deviation (SD) of recovery coefficients was calculated to evaluate the variability of PVE correction across different regions. Small lesions exhibited greater variability in RCs, reflecting the challenge of accurately correcting for the PVE in these regions. For example, lesions with diameters of less than 2 cm had an average standard deviation of ±0.15, indicating a relatively high degree of uncertainty in their recovery coefficients. In contrast, larger regions, such as the liver and heart, showed much lower variability, with standard deviations of ±0.05 and ±0.07, respectively. This highlights the higher reliability of PVE correction for larger organs.

Linear regression analysis was performed to examine the relationship between lesion size and recovery coefficient. A strong inverse correlation was found between lesion size and RC, with smaller lesions demonstrating progressively lower RC values. For instance, lesions with diameters of 1 cm had an average RC of 0.60, while those with diameters of 3 cm showed an average RC of 0.85. This relationship emphasizes the difficulty in accurately quantifying small lesions due to the PVE, even after applying correction factors.

Furthermore, the effect of slice thickness on RC variability was analyzed. A smaller slice thickness (improved resolution) consistently reduced the variability in RCs for small lesions. For example, for a 1.5 cm lesion located in the liver, the RC measured at a slice thickness of 10 mm had a standard deviation of ±0.10, whereas at 2.5 mm slice thickness, the standard deviation reduced to ±0.05. This suggests that higher-resolution PET scans provide more consistent and accurate results, particularly for smaller regions.

Example of Clinical Implication – Small Lung Nodule:

To illustrate the clinical relevance of these findings, consider a patient with a small lung nodule (approximately 2 cm in diameter) suspected of being malignant. In clinical practice, the accurate

measurement of tracer uptake in such lesions is critical for assessing the malignancy and determining the treatment approach. Without partial volume effect correction, the nodule might appear to have lower activity than it actually does, potentially leading to a false-negative diagnosis.

In our phantom study, the 2 cm lesion, scanned at a 10 mm slice thickness, exhibited an RC of 0.70, significantly underestimating the true activity concentration. However, with the application of RC correction based on our phantom-derived coefficients, the corrected RC for the 2 cm lesion was 0.85, which is a more accurate representation of the true activity concentration. This correction could directly impact the clinical management of the patient, ensuring that the lesion is not underestimated in terms of metabolic activity, and thus improving the accuracy of the diagnosis.

Overall Findings:

- Small lesions (≤2 cm) suffer significant underestimation of activity due to the PVE, with RCs ranging from 0.6 to 0.8.
- Large organs, such as the liver and heart, show minimal effects from PVE, with RCs close to 1.0.
- Spatial resolution plays a critical role in improving recovery coefficients, especially for small lesions, with higher resolution (2.5 mm slice thickness) yielding a 10-15% improvement in RC compared to lower resolution (10 mm slice thickness).
- Variability in RCs is greater for small lesions, with larger lesions showing more consistent and reliable results.
- Recovery coefficients derived from the phantom are crucial for improving the accuracy of small lesion quantification, with potential applications in oncology, cardiology, and neurology.

These findings highlight the importance of partial volume effect correction in PET/CT imaging, particularly for small lesions that may otherwise be mischaracterized. The calculated recovery coefficients provide a valuable tool for improving the quantitative accuracy of PET scans, enhancing diagnostic confidence, and optimizing treatment decisions. This approach is especially relevant in oncology, where precise quantification of tumor activity is essential for effective treatment planning and monitoring.

DISCUSSION

Impact of Partial Volume Effect:

The results of this study confirm that the PVE significantly affects the quantification of small lesions in PET/CT imaging. Smaller regions, such as tumors or nodules, suffer from underestimation of tracer uptake, which can hinder accurate diagnosis and treatment planning. This effect is particularly pronounced at lower spatial resolutions, where the smearing of activity from adjacent tissues is more pronounced.

Recovery Coefficients as a Corrective Measure:

The use of recovery coefficients for PVE correction proved to be effective in compensating for the underestimation of activity in small regions. By applying the RCs to the measured activity concentrations, we were able to obtain more accurate representations of tracer uptake, especially in smaller lesions. This correction method is essential for improving the diagnostic accuracy of PET/CT scans in oncology, cardiology, and neurology.

Limitations and Future Work:

One limitation of this study is that the anthropomorphic phantom, while realistic, cannot perfectly replicate all patient-specific variations in anatomy and physiology. Further studies are needed to assess the effectiveness of RCs in clinical populations, where patient-specific factors may introduce additional variability. Additionally, future work could explore the development of real-time PVE correction algorithms that integrate directly into clinical PET/CT workflows.

CONCLUSION

This study demonstrates that recovery coefficients derived from a customized anthropomorphic body phantom can significantly improve the accuracy of PET/CT imaging by correcting for the partial volume effect. The findings highlight the importance of high spatial resolution in mitigating the PVE, particularly for small lesions. The calculated RCs can serve as a valuable tool for improving quantitative PET/CT imaging, enhancing the clinical utility of PET scans in diagnosing and managing cardiovascular and oncological conditions.

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