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Analysis Absorbed Dose Sensitivity of 18F-FDG to Abdominal Organ Mass Variation Using MIRDcalc

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Abstract

18F-fluorodeoxyglucose Positron Emission Tomography (PET) using ^{18}F-fluorodeoxyglucose (^{18}F-FDG) is widely used in nuclear medicine. Accurate estimation of organ absorbed dose is important for patient safety and protocol optimization. However, standard dosimetry methods based on reference computational phantoms may not fully represent individual anatomical variability, particularly organ mass differences that influence absorbed dose estimation.This study aimed to analyze the sensitivity of absorbed dose to abdominal organ mass variations for ^{18}F-FDG. A computational dosimetry simulation study was performed using MIRDcalc and the ICRP 133 adult male reference phantom to evaluate simultaneous mass variations of six abdominal organs within a ±50% range. A quadratic relationship was found between mass change and average absorbed dose (R^2=0.9928). Dose decreased by 8.5% at +20% mass and increased by 9.2% at −20% mass. The small intestine showed the highest sensitivity (S=−0.45). Organ mass variation substantially influences absorbed dose estimates in simulation-based ^18F-FDG dosimetry. Further studies incorporating patient imaging data are required for clinical validation.

Keywords: Absorption Dose, 18F-FDG, Nuclear Medicine, MIRDcalc.

INTRODUCTION

Positron Emission Tomography (PET) imaging is one of the main modalities in nuclear medicine. PET with the radiopharmaceutical ^{18}F-Fluorodeoxyglucose (^{18}F-FDG) is widely employed in oncology, neurology, and cardiology diagnostics (Basu et al., 2011; Boellaard, 2009; Glaudemans et al., 2013). The working principle of PET is to detect the distribution of radioactive substances within the patient's body and evaluate the biodistribution of the administered radiopharmaceutical (Rasyada et al., 2025). Radiopharmaceuticals emit radiation that is detected by PET scanners. Internal radiation originating from adjacent organs cannot be avoided and must be considered to obtain accurate absorbed dose estimates and dose distribution within patient organs (Bolch et al., 2009; Salvatori et al., 2022).

In clinical applications, 1⁸F-FDG acts as a glucose analog that is actively accumulated by cells with high glycolysis rates, such as malignant tumor cells, brain tissue, and myocardium. This accumulation property causes the distribution of radionuclides in the body to be very dynamic and heterogeneous. The emission of positrons by Fluorine-18 is followed by an annihilation process when the positrons encounter free electrons in the surrounding tissue. This annihilation process produces two gamma photons with energies of 511 keV each that move in opposite directions. While the gamma photons are utilized for imaging by the PET detector, some of the photon energy and the kinetic energy of the emitted positrons are absorbed by the source organ itself and the surrounding target organs . The distribution and absorption of radiation doses by patients is one aspect of patient safety and must comply with the As Low As Reasonably Achievable (ALARA) principle so as not to harm patients and to enable the development of radiopharmaceuticals (Nenot et al., 2009, Rasyada et al., 2025).

The MIRDcalc software, developed by the Medical Internal Radiation Dose (MIRD) Committee, is used to estimate organ absorbed doses in nuclear medicine. MIRDcalc uses an anthropomorphic phantom approach that complies with the International Commission on Radiological Protection (ICRP) standards in ICRP Publication 133 (Bolch et al., 2016).

The MIRDcalc software implements the Medical Internal Radiation Dose (MIRD) schema by utilizing S-values (absorbed dose per unit cumulated activity) derived from reference computational phantoms, enabling rapid and standardized internal dosimetry calculations. Although reference phantom-based tools such as MIRDcalc and IDAC-Dose provide practical and reproducible dose estimates, they rely on standardized anatomical models that may not adequately represent individual patient variability. The ICRP adult male and female reference phantoms were developed from average anatomical characteristics and therefore cannot fully account for variations in organ geometry, body habitus, and organ mass observed in clinical populations (Ban et al., 2011).

Among these anatomical factors, organ mass variation is particularly important because it directly influences the amount of radiation energy absorbed per unit mass. This issue is especially relevant for abdominal organs, including the liver, kidneys, spleen, stomach, small intestine, and colon, which are among the principal organs involved in ^{18}F-FDG biodistribution Boellaard, 2009; Glaudemans et al., 2013). The masses of these organs vary considerably among individuals due to genetic factors, nutritional status, pathological conditions, and hydration status (Charubala, 2025). Consequently, the use of standard reference phantoms may lead to overestimation or underestimation of absorbed doses, thereby affecting radiobiological risk assessment and imaging protocol optimization (Dewaraja et al., 2012; Salvatori et al., 2022; Stabin, 2008).

Previous studies have primarily focused on the development, validation, and comparison of phantom-based dosimetry software or on patient-specific dosimetry approaches using individualized imaging data. However, the quantitative impact of systematic abdominal organ mass variation on absorbed dose estimation in ^{18}F-FDG PET using the MIRDcalc platform remains insufficiently investigated. In particular, the relative sensitivity of individual abdominal organs to mass changes and the resulting effects on self-dose and cross-dose contributions have not been comprehensively evaluated.

To address this knowledge gap, this study investigated the effect of simultaneous abdominal organ mass variations on absorbed dose estimation in ^{18}F-FDG PET dosimetry using MIRDcalc and the ICRP 133 adult male reference phantom. The masses of the liver, kidneys, spleen, stomach, small intestine, and colon were varied simultaneously by ±10%, ±20%, ±30%, ±40%, and ±50% relative to their reference values. The study aimed to determine how changes in abdominal organ mass influence absorbed dose estimates and organ dose sensitivity (Bednarz, 2023; Sgouros & Hobbs, 2014). Specifically, this study addressed the following research questions: (1) How do simultaneous abdominal organ mass variations affect absorbed dose estimation in ^{18}F-FDG PET dosimetry? and (2) Which abdominal organs exhibit the greatest sensitivity to mass variation? We hypothesized that absorbed dose estimates would vary inversely with organ mass and that the magnitude of this effect would differ among abdominal organs.

METHODS

DATA AND SIMULATION

This study used MIRDcalc version 1.0 as the primary platform for internal radiation dosimetry simulations. MIRDcalc is a web-based dosimetry application developed by the Medical Internal Radiation Dose (MIRD) Committee that implements standardized absorbed dose calculations based on the MIRD schema. Simulations were performed using the Adult Male reference phantom from ICRP Publication 133, which was selected as a standardized representation of human anatomy (Snyder, 1975). The radionuclide used in all simulations was ^{18}F-FDG, and organ-specific time-integrated activity coefficient (TIAC) values were obtained from the default ^{18}F-FDG biokinetic dataset available in the MIRDcalc library. The abdominal organs included in the dosimetric calculations were the liver, kidneys, spleen, stomach, small intestine, and colon. The right and left kidneys were treated as a combined organ according to the organ definition available in the MIRDcalc phantom. Absorbed dose estimates (mGy/MBq) were generated using the MIRD schema and phantom-based S-values and subsequently exported using the MIRDcalc data export function for further analysis in Microsoft Excel (Snyder, 1975).

To evaluate the influence of anatomical variability on absorbed dose estimation, simultaneous mass variations were applied to all abdominal organs under investigation. Organ masses were modified by −50%, −40%, −30%, −20%, −10%, +10%, +20%, +30%, +40%, and +50% relative to the reference masses defined in the ICRP 133 adult male phantom. Positive variations represented organ enlargement, whereas negative variations represented organ mass reduction. All organ masses were varied simultaneously at each variation level, while all other simulation parameters were maintained constant. This approach was selected to evaluate the overall dosimetric response of the abdominal organ system to anatomical mass variability commonly observed in clinical populations (Charubala, 2025).

The radiopharmaceutical used in this study was ^{18}F-FDG, one of the most widely applied tracers in clinical PET imaging (Boellaard, 2009; Glaudemans et al., 2013). To isolate the effect of organ mass variation on absorbed dose estimation, TIAC values were assumed to remain constant throughout all simulation scenarios. Under this assumption, changes in absorbed dose were attributed solely to variations in organ geometry and mass rather than differences in radiopharmaceutical uptake or biological clearance. Consequently, the analysis primarily reflects the dosimetric impact of anatomical variability on self-dose and cross-dose components. While this assumption facilitates systematic sensitivity analysis, it does not account for inter-patient variability in ^{18}F-FDG biodistribution and uptake kinetics. Therefore, the results should be interpreted as representing the influence of anatomical mass variation under standardized biokinetic conditions and may underestimate the additional uncertainty associated with patient-specific uptake variability (Ban et al., 2011; Snyder, 1975)

After each simulation, absorbed dose data were extracted and analyzed using Microsoft Excel. Graphical analysis and curve fitting were performed to evaluate the relationship between organ mass variation and absorbed dose, and sensitivity coefficients were calculated to quantify the response of each abdominal organ to mass changes.

CALCULATION OF ABSORPTION DOSE AND ORGAN SENSITIVITY

Each organ and its mass variation was calculated based on the percentage change in relative absorption dose compared to the initial condition (Bolch et al., 2009). The calculation was performed using Equation (1).

$$\%\Delta D = \frac{D_{mod} - D_{reff}}{D_{reff}} \times 100\% \qquad (1)$$

$\%\Delta D$ = relative dose change, D_{mod} = absorbed dose per organ mass variation, and D_{reff}= dose at initial organ mass.

The organ sensitivity coefficient to mass change is defined as the ratio between the relative change in average dose and the relative change in average mass within the range of variation studied (± 50%) (Andersson et al., 2017). Calculations are performed using Equation (2).

$$S = \frac{(\%\Delta D)_{avg}}{(\%\Delta M)_{avg}} \times 100\% \qquad (2)$$

S = organ sensitivity, $(\%\Delta D)_{avg}$ = average relative dose change value for each variation in organ mass, and $(\%\Delta D)_{avg}$ = average percentage change in mass.

RESULTS AND DISCUSSION

THE EFFECT OF MASS CHANGES ON AVERAGE ABDOMINAL DOSE

Based on computational simulations applied simultaneously to abdominal organs, a consistent shift pattern in the average absorbed dose values was obtained. A graph showing the relationship between changes in abdominal mass and changes in average dose can be seen in Figure 1.

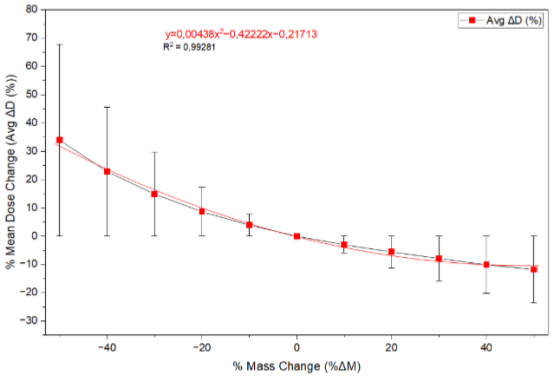

Figure 1. The relationship between changes in abdominal mass and changes in average dose

The simulations demonstrated that simultaneous variations in abdominal organ mass had a substantial effect on the average absorbed dose across the abdominal organs. The results showed a consistent inverse relationship between organ mass and absorbed dose, whereby decreasing organ mass resulted in an increase in the average absorbed dose, whereas increasing organ mass produced a reduction in absorbed dose. For example, a 20% decrease in organ mass increased the average absorbed dose by approximately 9.2%, while a 20% increase in organ mass reduced the average absorbed dose by approximately 8.5%. Similar trends were observed across the entire range of simulated mass variations.

A strong quadratic relationship was identified between the percentage change in organ mass (%ΔM) and the percentage change in average absorbed dose (%ΔDavg), with a coefficient of determination (R^2) of 0.99281. This high R^2 value indicates that the quadratic model accurately describes the relationship between anatomical mass variation and absorbed dose response within the simulated conditions. The relationship between %ΔM and %ΔDavg can be expressed by the following equation:

$$y = 0.0044\, x^2 - 0.4222\, x - 0.2171$$

$$R^2 = 0.9928$$

This pattern indicates that the relationship between organ mass and absorbed dose is not perfectly linear but follows a quadratic response. As organ mass increases, the absorbed energy is distributed over a larger tissue volume, resulting in a reduction in dose per unit mass. Conversely, when organ mass decreases, the same amount of deposited energy is concentrated within a smaller volume, producing a proportionally larger increase in absorbed dose. This asymmetry is evident from the simulation results: a +20% mass variation reduced the average absorbed dose by approximately 8.5%, whereas a −20% mass variation increased the average absorbed dose by approximately 9.2%. The slightly greater response observed for mass reduction reflects the nonlinear dependence of absorbed dose on organ mass and suggests that smaller organs are more sensitive to anatomical variations. Such behavior is consistent with the influence of self-dose geometry and energy deposition mechanisms incorporated in the MIRD formalism (Hobbs et al., 2013; Lassmann et al., 2011).

The negative linear coefficient indicates that an increase in abdominal organ mass generally leads to a reduction in the average absorbed dose. This phenomenon occurs because the emitted radiation energy becomes distributed over a larger tissue volume, thereby decreasing the energy deposited per unit mass. However, the positive quadratic term reveals that the rate of dose reduction is not constant across the entire range of mass changes. Instead, the relationship becomes progressively nonlinear at larger deviations from the reference mass, indicating increasingly complex interactions between photon attenuation, organ geometry, and energy deposition.

The quadratic trend also suggests that both mass increases and mass reductions can substantially alter abdominal dosimetry, particularly when the anatomical variation is large. Smaller abdominal masses tend to produce higher average absorbed doses due to reduced attenuation and smaller target volume, whereas larger masses generally dilute the absorbed energy and lower the dose concentration. These findings emphasize the importance of considering patient-specific anatomical characteristics in internal dosimetry calculations, especially in nuclear medicine procedures involving radiopharmaceutical distribution within the abdominal cavity (Hobbs et al., 2013; Lassmann et al., 2011).

Overall, the simulation results indicate that organ mass variability is a critical factor affecting absorbed dose estimation and should be incorporated into personalized dosimetric approaches to improve accuracy, optimize treatment planning, and enhance radiation safety.

ORGAN-SPECIFIC SENSITIVITY AND DOSE COMPONENTS

Figure 2 illustrates the relationship between the percentage change in mass (%ΔM) and the percentage change in dose (%ΔD) for each abdominal organ studied, namely the liver, kidneys, spleen, stomach, small intestine, and colon.

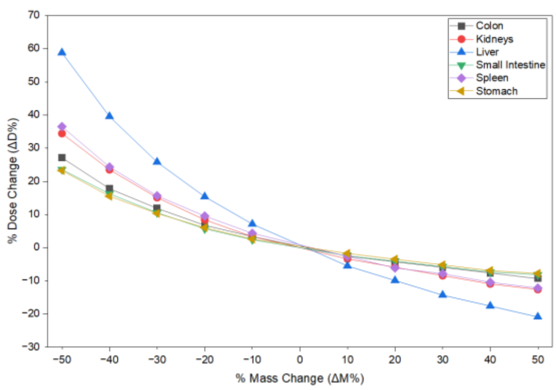

Figure 2. Relationship between changes in mass and changes in dose per abdominal organ

Based on Figure 2, all abdominal organs demonstrated an inverse relationship between organ mass and absorbed dose, with dose values increasing as organ mass decreased and decreasing as organ mass increased. The liver exhibited the largest absolute response to mass variation, with the absorbed dose increasing by nearly 60% at a −50% mass reduction. This pronounced response is consistent with the relatively high ^{18}F-FDG uptake in the liver and its dominant self-dose contribution, causing deposited energy to become concentrated within a smaller tissue volume as organ mass decreases. In contrast, the small intestine and colon showed the highest sensitivity to mass variation, with sensitivity coefficients of −0.45 and −0.40, respectively, compared with −0.38 for the liver. The steeper dose-response curves observed in these organs indicate a stronger dependence of absorbed dose on anatomical mass changes. Meanwhile, the stomach exhibited a more gradual response to mass variation, suggesting a relatively greater influence of cross-irradiation from surrounding tissues. These quantitative differences demonstrate that organ-specific dose responses are governed by a combination of organ mass, anatomical geometry, self-dose contribution, and radionuclide biodistribution characteristics.

To further explain the mechanisms underlying these dose patterns, the absorbed dose was divided into self-dose, originating from radionuclide accumulation within the source organ, and cross-dose, resulting from radiation emitted by neighboring organs. Figure 3 presents the dose decomposition under baseline conditions using the ICRP reference mass model, illustrating how variations in organ geometry and spatial arrangement influence the relative contribution of internal and external irradiation components across the abdominal cavity.

SELF-DOSE AND CROSS-DOSE CONTRIBUTIONS

Analysis of the baseline condition using the ICRP 133 reference phantom revealed differences in the relative contributions of self-dose and cross-dose among the abdominal organs (Figure 3). Self-dose and cross-dose components were obtained from the MIRDcalc output by separating dose contributions originating from activity within the target organ itself and from activity accumulated in neighboring source organs. The liver exhibited the highest self-dose contribution (approximately 70%), indicating that most of the absorbed dose originated from ¹⁸F-FDG accumulated within the liver. In contrast, the kidneys showed a dominant cross-dose contribution (approximately 60%), reflecting the influence of radiation emitted from surrounding abdominal organs and their close anatomical proximity within the abdominal cavity (Bolch et al., 2009, 2016).

These findings indicate that inter-organ radiation interactions contribute substantially to absorbed dose estimates and should be considered when evaluating the dosimetric impact of anatomical variations. The observed cross-dose contribution in the kidneys further suggests that simultaneous assessment of abdominal organ groups may provide a more comprehensive representation of dose distribution than analyses focused solely on individual organs.

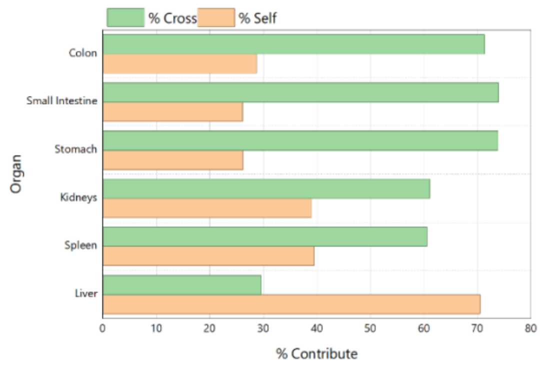

Figure 3. Contribution of self-dose and cross-dose at baseline conditions

Figure 4 shows the change in the self-dose ratio (self/total) in relation to mass variation. An increase in mass causes a decrease in the self-dose ratio for all organs, which means that the contribution of cross-dose becomes more dominant as the organ volume increases. The most significant decrease occurs in the small intestine and colon, in line with the high contribution of cross-dose to these organs. This phenomenon can be explained by an increase in the volume of radiation sources that emit energy to surrounding organs.

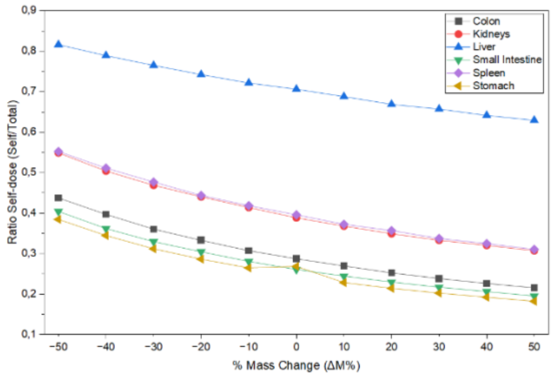

Figure 4. Change in self-dose ratio versus mass variation

DOSE SENSITIVITY TO ORGAN MASS VARIATION

The sensitivity coefficient (S) is defined as the ratio between the relative change in absorbed dose and the relative change in organ mass, providing a quantitative measure of how strongly dose estimation responds to anatomical variations. A higher sensitivity coefficient indicates that small changes in organ mass produce larger changes in absorbed dose, whereas lower values indicate reduced dependence of dose on mass variation. Figure 5 illustrates the sensitivity curve as a function of mass change, demonstrating the relationship between increasing or decreasing organ mass and the corresponding variation in absorbed dose.

The curve reveals that dose sensitivity is not always linear across all mass ranges, suggesting that anatomical differences among patients may significantly influence internal dosimetry calculations. In particular, organs with smaller masses tend to exhibit greater sensitivity because the deposited energy is distributed within a smaller tissue volume, resulting in higher absorbed dose values. Conversely, larger organ masses generally reduce dose concentration, leading to lower sensitivity. These findings highlight the importance of incorporating patient-specific anatomical parameters into dosimetric models to improve the accuracy and reliability of personalized nuclear medicine assessments.

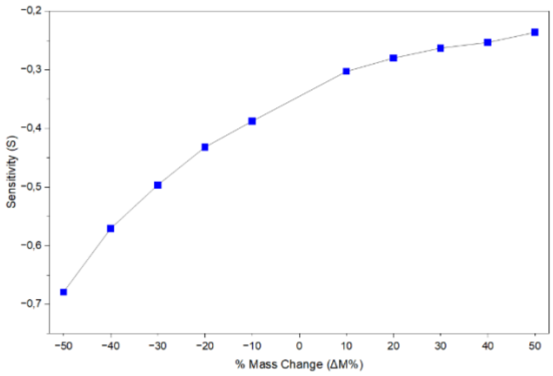

Figure 5. Dose sensitivity to changes in mass

The sensitivity graph shows consistently negative values, confirming the inverse correlation between mass and dose. Sensitivity tends to be more stable over a wide range of variations, but increases sharply as organ mass decreases. This indicates that errors in mass estimation in patients with small organs will result in much greater errors in dose estimation than in patients with standard organ mass.

Table 1. Sensitivity coefficients (S) of abdominal organs to mass variation

No	Organ	Sensitivity (S)
1	Liver	-0,38
2	Kidney	-0,35
3	Spleen	-0,28
4	Stomach	-0,32
5	Small Intestine	-0,45
6	Colon	-0,40

Based on Table 1, the small intestine exhibited the highest sensitivity to mass variation ($S = -0.45$) among the abdominal organs evaluated. This result indicates that absorbed dose estimates in the small intestine are more strongly affected by anatomical variability than those in the other abdominal organs studied. Therefore, patient-specific anatomical information may be particularly important for improving dosimetric accuracy in highly sensitive organs and for supporting radiation protection optimization in accordance with the ALARA principle (Sgouros & Hobbs, 2014)

CONCLUSION

This simulation study showed that abdominal organ mass variation affects absorbed dose estimation in ^{18}F-FDG PET dosimetry using the MIRDcalc platform. Simultaneous organ mass variations produced a strong quadratic relationship between mass variation and average absorbed dose, indicating that dosimetric response is influenced by both tissue volume and inter-organ radiation interactions. Increasing organ mass reduced absorbed dose because radiation energy was distributed across a larger tissue volume, whereas decreasing organ mass increased absorbed dose concentration. These findings provide quantitative insight into the influence of anatomical mass variation on internal dose estimates. However, the results were obtained using the ICRP 133 Adult Male reference phantom and under the assumption of constant time-integrated activity coefficients (TIACs). Therefore, the findings should be interpreted within the context of these standardized simulation conditions and may not fully represent patient-specific anatomical characteristics or radiopharmaceutical uptake variability.

Among the evaluated organs, the small intestine exhibited the highest sensitivity to mass variation, followed by the colon and liver. In addition, increasing organ mass reduced the self-dose ratio and enhanced the contribution of cross-dose interactions. These findings demonstrate that internal radiation dose estimation is strongly affected by anatomical variability and cannot rely solely on standard reference phantoms.

The present findings suggest that incorporating patient-specific anatomical information into internal dosimetry calculations may improve the accuracy of absorbed dose estimation, particularly for organs that exhibit high sensitivity to mass variation. Therefore, individualized dosimetry approaches based on anatomical information obtained from CT or MRI may provide a useful framework for refining dose assessments and supporting optimization strategies consistent with the ALARA principle.

However, this study was based on simulations using the ICRP 133 Adult Male reference phantom and assumed constant time-integrated activity coefficients (TIACs). Consequently, the results do not account for patient-specific variations in organ geometry, radiopharmaceutical uptake, or biokinetic behavior. Future studies should validate these findings using CT- or MRI-derived organ masses from individual patients and compare the resulting absorbed dose estimates with those obtained from reference phantom-based calculations. The integration of patient-specific anatomical and physiokinetic data will enable a more comprehensive evaluation of personalized dosimetry approaches in clinical nuclear medicine practice.

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