

ORIGINAL ARTICLE

Correlation between tumor oxygenation and ^{18}F -fluoromisonidazole PET data simulated based on microvessel images

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Abstract

Background. Assessing hypoxia with oxygen probes provides a sparse sampling of tumor volumes only, bearing a risk of missing hypoxic regions. Full coverage is achieved with positron emission tomography (PET) using the tracer ^{18}F -fluoromisonidazole (FMISO). In this study, the correlation between different FMISO PET imaging parameters and the median voxel PO_2 (median PO_2) was analyzed. A measure of the median PO_2 characterizes the microenvironment in consistency with probe measurements. **Material and methods.** Tissue oxygenations and FMISO diffusion-retention dynamics were simulated. Transport of FMISO and O_2 molecules into and out of tissue was modeled by vessel maps derived from histology of head-and-neck squamous cell cancer xenograft tumor lines. Parameter sets were evaluated for 300 distinct $2 \times 2 \text{ mm}^2$ vessel configurations, including median PO_2 and two FMISO PET parameters: F_{H} denotes the sub-regional signal four hours post injection (pi) and $F_{\text{H/P}}$ denotes the ratio between F_{H} and the time-averaged signal 0–15 min pi. Correlations between O_2 and FMISO parameters were evaluated. A receiver operating characteristics (ROC) analysis was performed, regarding the accuracy of F_{H} and $F_{\text{H/P}}$ in identifying voxels with median $\text{PO}_2 < 2.5 \text{ mmHg}$. **Results.** In hypoxic sub-regions, the correlation between F_{H} and median PO_2 is low ($R^2 = 0.37$), while the correlation between $F_{\text{H/P}}$ and median PO_2 is high ($R^2 = 0.99$). The ROC analysis showed that hypoxic regions can be identified using $F_{\text{H/P}}$ with a higher diagnostic accuracy ($\text{YI} = \text{sensitivity} + \text{specificity} - 1 = 1.0$), than using F_{H} alone ($\text{YI} = 0.83$). Both FMISO parameters are moderately effective in identifying hypoxia on the microscopic length scale ($\text{YI} = 0.63$ and 0.60). **Conclusions.** A combination of two FMISO PET scans acquired 0–15 min and four hours pi may yield an accurate measure of the median PO_2 in a voxel ($F_{\text{H/P}}$). This measure is comparable to averaged oxygen probe measurements and has the advantage of covering the entire tumor volume. Therefore, it may improve the prediction of radiotherapy outcome and facilitate individualized dose prescriptions.

Radiotherapy (RT) is less effective in hypoxic tumors. Clinical studies have shown that therapy response correlates with tumor oxygen concentrations (PO_2) measured with Eppendorf electrodes [1,2]. Oxygen probes yield an accurate measure of the local PO_2 and the measurements are confined to a very small tissue volume [3]. However, they are invasive and limited to a few linear tracks across a tumor, i.e. it is impossible to assess the oxygenation in the entire tumor volume and as a consequence there is a risk

of missing severely hypoxic regions. These aspects may limit the applicability of probe measurements to derive a reliable overall prognosis of RT outcome and to guide the adaption of RT dose prescriptions to the local degrees of hypoxia-associated radioresistance (hypoxia dose painting [4,5]).

A three-dimensional assessment of tumor hypoxia is possible with positron emission tomography (PET) imaging using hypoxia tracers such as ^{18}F -fluoromisonidazole (FMISO). Clinical studies have shown that

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hypoxia PET imaging may be applicable to predict the overall RT response in different tumor entities including head-and-neck cancer [6–8]. However, direct voxel-based comparisons between hypoxia PET data and PO_2 measurements using optical oxygen probes in preclinical tumor models were contradictory [9,10]. The authors hypothesized that a possible explanation is that oxygen probes assess the PO_2 in vital and necrotic tissue alike, while FMISO accumulates in vital cells only. Therefore, in severely hypoxic voxels with a large amount of necrosis, the ambiguous situation may occur that a low average PO_2 coincides with a very low tracer accumulation. Similar observations were made in clinical tumors by a study comparing FMISO PET and measurements with an Eppendorf electrode in different tumor entities [11].

This indicates that an assessment of the voxel-based PO_2 by means of FMISO PET imaging with an accuracy comparable to that of probe measurements is intricate. It may require more comprehensive imaging protocols and dedicated tools for data analysis than an overall prognosis of RT outcome based on a single PET scan acquired several hours after tracer injection (pi).

The purpose of this study was to identify an FMISO PET imaging parameter that is an accurate measure of the median voxel PO_2 as assessed by direct probe measurements. This parameter must overcome the limitations of imaging the FMISO accumulation at a single time point and may be useful to effectively guide hypoxia dose painting. In addition, its acquisition should be as simple as possible. Here, two parameters were considered that require either a single late PET scan (4 h pi) or the combination of a late scan and one immediately after tracer injection (0–15 minutes pi). The correlation between these parameters and the median of the underlying PO_2 distribution was analyzed. The analysis was based on computational simulations of: 1) the tissue oxygenation; and subsequently, 2) the FMISO diffusion-accumulation dynamics for many different histology-derived microvessel arrangements [12].

Material and methods

Tissue microsections and tumor microvessel maps

In order to model the flux of O_2 and FMISO molecules into and out of tissue in a biologically realistic manner, vessel maps were derived from tumor tissue histology. As described earlier [13], frozen tissue sections from human head-and-neck squamous cell cancer (SCCHN) xenograft tumor lines were immunohistochemically (IHC) stained for endothelial structures with 9F1 (rat monoclonal to mouse endothelium, Department of Pathology, Radboud University Nijmegen Medical Centre, Nijmegen,

The Netherlands). Subsequently, the sections were scanned using a digital image analysis system, resulting in gray-scale images of the fluorescent signal. In this study, five images from different tumors with a total area of 133 mm² were converted into vessel maps. The images were selected from a large database so that the vessel patterns varied strongly among as well as within the maps, ranging from very dense to sparse and inhomogeneous distributions. A total of 300 sub-regions with dimensions of 2 × 2 mm² were placed in the maps at random locations. In these sub-regions, the studied O_2 and FMISO parameters were calculated from the simulated data.

Modeling and simulation of O_2 and FMISO

A tool to perform computer simulations of the FMISO diffusion-retention dynamics in multiple steps was used in this study. Its basic working principle is schematically shown in Supplementary Figure 1 available online at <http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.812796>. The applied diffusion-reaction equations, simulation method and parameter values were described in detail earlier [12]. Briefly, equilibrium oxygen partial pressure (PO_2) distributions are calculated for a given vessel map. The applied model accounts for the supply of oxygen across capillary membranes, its distribution in tissue and its consumption by tumor cells. A Michaelis-Menten relationship describes that cells decrease their oxygen consumption in line with a decreasing amount of available oxygen [14]. Subsequently, the PO_2 distributions are used to calculate local FMISO binding rates. Binding rates are modeled to increase with decreasing PO_2 , up to a sharp drop at very low PO_2 . This drop accounts for cell death under extreme oxygen and glucose deprivation. In this way it is considered that FMISO is reduced in vital cells only. These assumptions agree qualitatively with Pimonidazole IHC in SCCHN xenografts [15]. Finally, by applying the PO_2 -dependent local binding rates, FMISO supply, diffusion and retention are simulated in the same vessel map as the PO_2 . By integrating the simulated FMISO concentrations in a specific sub-region, pseudo-PET voxel signals can be derived at different timepoints pi. Dividing these signals by the blood tracer concentration yields tumor-to-blood (T:B) ratios.

Simulated macroscopic O_2 and FMISO parameters

In each sub-region the median oxygen partial pressure (median PO_2) was calculated. Two simulated FMISO parameters were calculated in each sub-region: 1) the mean FMISO concentration four hours pi, $F_H = c(t = 4 \text{ h pi})$; and 2) the ratio between F_H and the average concentration 0–15 minute pi, $F_{H/P} = c(t = 4 \text{ h pi}) / \overline{c(t)}_{0-15 \text{ min}}$. The second parameter

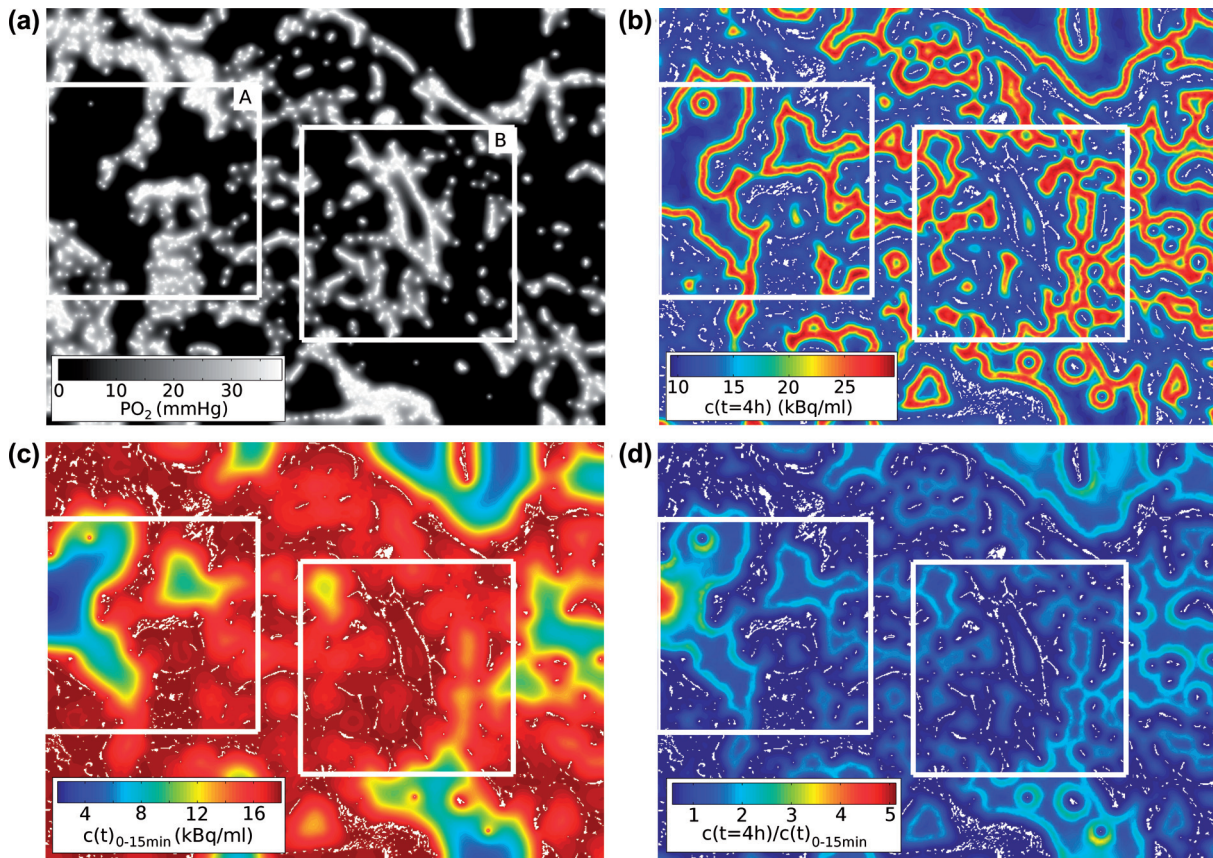


Figure 1. (a) Steady state PO_2 distribution for a 5.3×3.9 mm² vessel map including two randomly placed 2×2 mm² sub-regions (A, B). (b) Corresponding distribution of FMISO 4 h pi. Sub-regional averaging yields F_H . Note the increasing retention with decreasing PO_2 until it is diminished by necrosis. Vessels are white. (c) Averaged early FMISO signal. (d) Ratio between the distributions shown in (b) and (c) yields $F_{H/P}$. The median PO_2 is substantially lower in sub-region A (9.4×10^{-3} mmHg) than in B (7.1×10^{-1} mmHg). Inconsistently, F_H is lower in A (15.0 kBq/ml) than in B (16.4 kBq/ml). $F_{H/P}$ is higher in A (1.05) than in B (1.00) and thus is consistent with median PO_2 .

can be interpreted as a measure of hypoxia-related tracer retention that is normalized by a simple measure of perfusion [16]. In this way, severely hypoxic regions containing much necrosis, in which small amounts of FMISO are retained, may nonetheless be correctly identified as having a low median PO_2 , as they are typically poorly perfused as well.

Correlations between oxygenation and FMISO PET

Scatter plots of median PO_2 against F_H as well as $F_{H/P}$ were created. Furthermore, a correlation analysis was performed between median PO_2 and the FMISO parameters. Coefficients of determination R^2 were calculated in a linear sense (Pearson coefficient) and from non-linear fits.

Hypoxic sub-regions were segmented from all sub-regions by applying various thresholds to the simulated FMISO parameters. This emulates the method commonly used to identify hypoxia in FMISO PET images. In a receiver operating characteristic (ROC) analysis it was assessed how reliably sub-regions with a median PO_2 below 2.5 mmHg can be identified when this

method is applied to F_H and $F_{H/P}$. In ROC curves, the true positive rate ($tpr = \text{sensitivity}$) was plotted against the false positive rate ($fpr = 1 - \text{specificity}$). The applied FMISO thresholds decrease along the curves. The area under the curves (AUC) and the Youden index ($YI = tpr - fpr$) were calculated as quality measures. Their values may range from 0.5 to 1 and 0 to 1 (no predictive value to strong predictive value), respectively. In a further step, the ROC analysis was also used to evaluate how well the FMISO parameters characterize the micro PO_2 values on the cellular level. In this case, each parameter represents a 60×60 matrix of underlying PO_2 values.

Results

Simulated oxygenations

Full simulations were performed for the five vessel maps. An example for a simulated equilibrium PO_2 distribution and the corresponding static FMISO micropattern four hours pi is shown in Figure 1a. The median micro PO_2 value of all maps was 10.0 mmHg and ranged from 0.0 mmHg to 40.0 mmHg. The micro PO_2 was calculated with a spatial resolution of

50 $\mu\text{m}/\text{pixel}$, which is comparable to Eppendorf electrodes [3]. Histograms of the microPO_2 within four selected sub-regions show distinct oxygenation patterns (Supplementary Figure 2 available online at <http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.812796>). The simulated sub-regional medianPO_2 ranged from 8×10^{-3} mmHg to 33.8 mmHg with a median of 7.0 mmHg.

Correlations between oxygenation and FMISO PET

In Figure 2a a scatter plot of medianPO_2 against F_H is shown. Each point represents a data pair from a specific sub-region. A high overall linear correlation coefficient R^2 of 0.95 was observed. This value reduces to 0.37 when the analysis is restricted to data pairs in the hypoxic range (i.e. $\text{medianPO}_2 < 10$ mmHg). However, a high accuracy is especially important in this range. In Figure 1 it is demonstrated for two selected sub-regions that the low FMISO retention in regions with a large amount of necrosis is an important reason for the low correlation between F_H and medianPO_2 in hypoxic tissue.

A plot of the medianPO_2 against the perfusion-normalized FMISO parameter $F_{H/P}$ is shown in Figure 2b. By visual inspection a well-defined non-linear relationship was found, especially in the hypoxic range. This was corroborated by fitting the function $f(x) = p_1/(p_2 + x)^{p_3} + p_4$ to the data. The resulting fit coefficients were $[p_1, p_2, p_3, p_4] = [568 \text{ mmHg}, 0.575, 10.0, -0.210 \text{ mmHg}]$. A coefficient of determination R^2 between medianPO_2 and $F_{H/P}$ of 0.98 was found for the overall data and of 0.99 for the data in the hypoxic range. This suggests that $F_{H/P}$ is a more accurate measure of the medianPO_2 than F_H .

ROC analysis

The ROC analysis of the diagnostic accuracies of the simulated FMISO parameters to identify hypoxia is shown in Figure 3. Clearly, sub-regions with a critical medianPO_2 below 2.5 mmHg are discriminated extremely well by $F_{H/P}$ ($\text{AUC} = 1.0$, optimum $\text{YI} = \text{tpr-fpr} = 1.0$), while F_H alone is less reliable ($\text{AUC} = 0.97$, $\text{YI} = 0.83$). The optimum threshold values were $F_{H/P} = 1.1$ and $F_H = 16.1 \text{ kBq/ml}$ ($\text{T:B} = 1.8$).

The ROC analysis with regard to the identification of microscopic hypoxia (microPO_2) based on the macroscopic FMISO parameters gave a slightly different picture. It resulted in AUC (optimum YI) of 0.88 (0.63) and 0.86 (0.60) for $F_{H/P}$ and F_H , respectively. These values are considerably lower than for the identification of sub-regions with a critical macroscopic medianPO_2 based on either of the FMISO parameters. Here, the optimum threshold values were $F_{H/P} = 1.0$ and $F_H = 15.5 \text{ kBq/ml}$ ($\text{T:B} = 1.7$).

Discussion

The results of this study outline how the fundamental limitations of FMISO PET imaging affect its value as a measure of the PO_2 in a voxel. The first limitation is that a macroscopic imaging modality is used to image hypoxia, which is a microscopic phenomenon. Therefore, the measured signal is an average over a very heterogeneous distribution of hypoxia levels on the microscopic length scale. Another important aspect is the ambiguous binding behavior of the FMISO molecule: it shows a low accumulation in severely hypoxic regions containing a large amount of necrosis. As a consequence, these regions cannot be distinguished

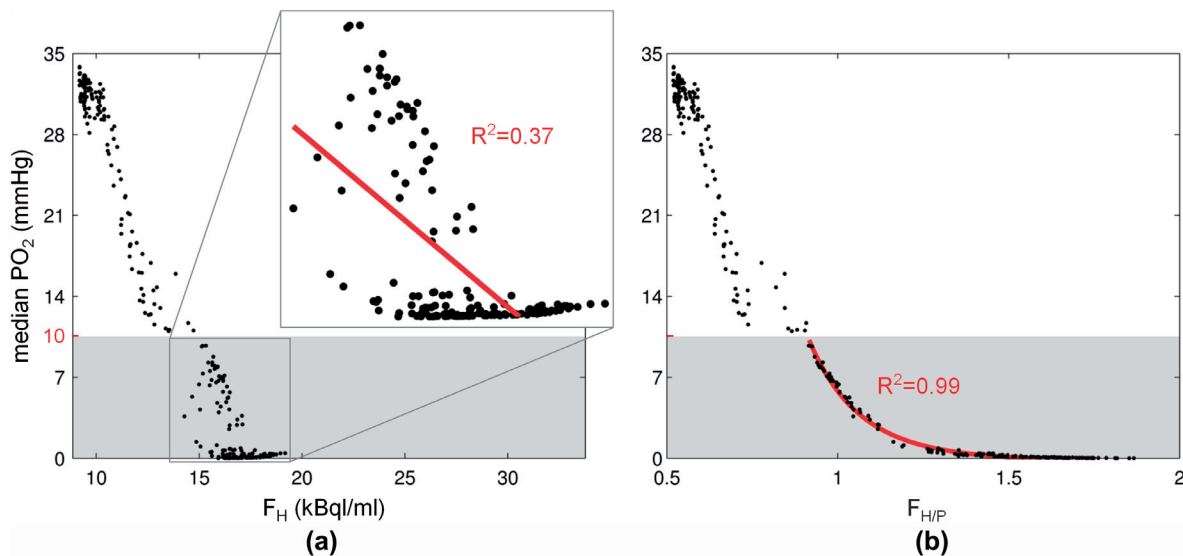


Figure 2. Scatter plots of medianPO_2 against (a) F_H and (b) $F_{H/P}$. Red lines are fits restricted to hypoxic sub-regions ($\text{medianPO}_2 < 10$ mmHg). Coefficients of determination R^2 for the restricted fits indicate a low correlation between medianPO_2 and F_H and a high correlation between medianPO_2 and $F_{H/P}$.

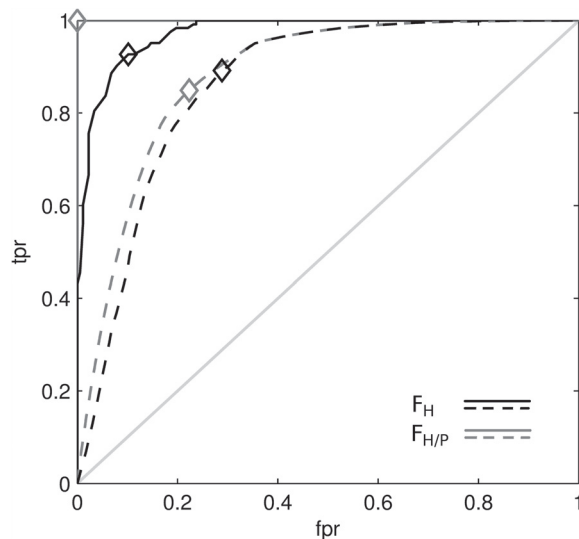


Figure 3. Receiver operating characteristic of $F_{H/P}$ (gray curves) and F_H (black curves) for the identification of hypoxia. Solid lines refer to the identification of a median $PO_2 < 2.5$ mmHg in macroscopic sub-regions. Dashed lines refer to the identification of micro $PO_2 < 2.5$ mmHg in the 60×60 PO_2 values underlying each FMISO parameter. Cut-off values applied to the FMISO parameters decrease along the curves from left to right. Optimum points are marked. The identification of critical median PO_2 is very sensitive and specific using $F_{H/P}$ (optimum YI = 1.0). Using F_H is less effective (YI = 0.83). Both parameters are moderately accurate in identifying critical micro PO_2 values (YI = 0.63 and 0.60).

from well-oxygenated regions in FMISO PET images acquired during the tracer uptake phase. These limitations have also been observed in preclinical tumor models using ^{18}F -FluoroazomycinArabinoside (FAZA) autoradiography and Pimonidazole IHC [17].

Here, a method was proposed to compensate the deficient tracer accumulation due to necrosis by incorporating supplementary information. For this purpose, the simulated PET signal during the FMISO wash-in phase (0–15 minute pi) was used, as it characterizes the vessel network in a voxel and therefore identifies poorly perfused voxels independently of the FMISO accumulation (cf. Figure 1c). The results show, that the proposed combined parameter $F_{H/P}$ is a much more accurate measure of the median PO_2 than the uptake parameter F_H alone. This indicates that $F_{H/P}$ characterizes the tissue microenvironment in a similar manner as measurements with oxygen probes. However, FMISO PET imaging overcomes the limitation of oxygen probes of sampling the PO_2 in small parts of a tumor only. These results corroborate a preclinical study correlating optical oxygen probe measurements with FMISO PET imaging, in which severely hypoxic voxels with low PO_2 readings presented low FMISO intensities two hours pi [9].

The large range of oxygenation levels that are averaged in a PET voxel signal cannot be recovered. This is demonstrated by the relatively low diagnostic

accuracy of F_H as well as $F_{H/P}$ with respect to the identification of micro PO_2 values below 2.5 mmHg. The accuracies simulated in this work are comparable to results from a preclinical study analyzing FMISO PET signals and oxygen probe readings on a voxel-by-voxel basis [10]. A moderate accuracy was reported for the identification of micro PO_2 values below 2.5 mmHg using the two hour pi equivalent to F_H acquired with a sub-millimeter resolution. As fully dynamic FMISO PET was performed in this study, the method offers a potential to validate the theoretical results of the present work.

Quantitative aspects of the results must be interpreted with great care. In a clinical setting, the correlations and diagnostic accuracies presumably are substantially lower than estimated here. There are a number of reasons for this. For instance, the achievable resolution in clinical PET imaging is lower than the edge length of 2 mm of the simulated sub-regions. Inter-patient variations of the tracer pharmacokinetics, such as tracer clearance and metabolite forming, also have an influence. Furthermore, image noise was not included in the analysis and simulations were performed in 2D. Though, as these factors influence F_H and $F_{H/P}$ alike, the general conclusion holds that the perfusion-normalized uptake parameter $F_{H/P}$ is a more accurate measure of the median PO_2 than the uptake parameter F_H alone.

The early acquisition interval of 0–15 minutes has not been varied in this study. It is well possible that a shorter scan provides identical information. The length and position of the interval can be optimized in a preclinical validation study combining spatially co-registered dynamical FMISO PET and oxygen probe measurements, which is technologically feasible [10]. A validation of the presented results is moreover needed, because not every biological effect can be accounted for by the simulation model. For example, the proposed parameter $F_{H/P}$ may be less accurate when tissue perfusion and hypoxia levels are uncoupled. This situation may arise in tissue regions that are dominated by hemoglobin deficient plasma flow. Such regions can be very hypoxic (high FMISO retention) and at the same time well perfused (high wash-in signal).

Incorporating the wash-in phase FMISO PET signal does not only allow to compensate the low tracer accumulation in severely hypoxic voxels, it may also yield a prediction of the development of the hypoxic microenvironment during RT, e.g. the reoxygenation potential of a tissue region [18]. This could explain why clinical results indicate that optimum timepoints for isolated uptake imaging might lie weeks into the course of therapy [6,19]. In contrast, a full kinetic analysis of dynamic FMISO PET data allows the estimation of treatment outcome prior to the initiation of

RT [16]. The parameter F_{HP} proposed here was designed to capture the essential information of dynamic FMISO PET imaging, i.e. the independent information from the tracer wash-in as well as the uptake phase, yet avoiding the complex acquisition and analysis of fully dynamic data. However, potential issues arising from patient repositioning between the two PET scans and subsequent image co-registration remain. Should this compromise the usefulness of the proposed method, moving the patient off the table between scans may be avoided by obtaining a perfusion measure from a ^{15}O -Water PET scan or a suitable MRI or DCE CT protocol in a combined scanner.

Conclusions

In this study, tissue oxygenations and FMISO diffusion-retention dynamics were computationally simulated. The correlation between simulated partial oxygen pressures and different FMISO PET parameters was analyzed. The results show that the median PO_2 in a PET voxel can be assessed with high accuracy by combining independent information from early (0–15 minutes pi) and late (four hours pi) FMISO PET scans. Using a late scan only is less accurate. Both methods recover the oxygenation on the cellular level with moderate accuracy.

Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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Supplementary material available online

Supplementary Figures 1–2