Three-dimensional T_1 mapping demonstrates the transfer of oxygen into cerebrospinal fluid during hyperoxia

Emma Biondetti[1,2], Davide Di Censo[1,2], Sara Pomante[1,2], Stefano Censi[1,2], Ekaterina Bliakharskaia[1,2], Manuela Carriero[1,2], Francesca Graziano[1,2], Alessandra Stella Caporale[1,2], Antonio Maria Chiarelli[1,2], and Richard Geoffrey Wise[1,2]

[1]Department of Neurosciences, Imaging and Clinical Sciences, University "G. D'Annunzio" of Chieti-Pescara, Italy, Chieti, Italy

[2]Institute for Advanced Biomedical Technologies, University "G. D'Annunzio" of Chieti-Pescara, Italy, Chieti, Italy

Corresponding author:
Emma Biondetti, PhD
Department of Neurosciences, Imaging and Clinical Sciences
Institute for Advanced Biomedical Technologies
University “G. D’Annunzio” of Chieti-Pescara
Via dei Vestini, 31 – 66100 Chieti – Italy
E-mail: emma.biondetti@unich.it

Abstract (max 194/200 words)

This study developed a non-invasive magnetic resonance imaging technique to investigate the transfer of oxygen into cerebrospinal fluid (CSF) in healthy subjects. Alterations in CSF T_1 (longitudinal relaxation time) were induced by 100% hyperoxia and measured using a 3D SPACE sequence at 3T in 20 subjects, thereby demonstrating oxygen diffusion from blood to CSF. T_1 mapping was performed at high resolution (0.9-mm isotropic) to capture anatomical details of the CSF spaces and was also repeated more rapidly at a lower resolution (3-mm isotropic) to capture the temporal dynamics of T_1 changes. Region-dependent reductions in T_1 were observed, indicating increased oxygen concentration. These occurred most prominently and rapidly in the cortical subarachnoid space, stabilising within approximately 7 minutes of initiating hyperoxia, suggesting that oxygen diffusion primarily occurs via pial arteries. Slower changes, commencing after approximately 10 minutes, occurred in the posterior lateral ventricles, where choroid plexus is found. In addition to providing insights into the structure of CSF and dynamics of blood-CSF oxygen exchange, this methodology could, in the future, offer a valuable tool for characterising the passive diffusion (oxygen permeability) properties of cerebral blood vessel walls, thereby providing a potential marker of cerebrovascular integrity.

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1 Introduction

There is growing interest in the magnetic resonance imaging (MRI) community in developing techniques to characterise the exchange dynamics between blood, cerebrospinal fluid (CSF) and the adjacent brain parenchyma, and to understand how these processes are regulated by the blood-brain barrier (BBB) and blood-CSF barrier (BCSFB).[1] Ultimately, the efficiency of these exchange mechanisms is considered essential for removing cerebral waste products, and alterations in permeability may reveal pathological modifications to these barriers.

In this context, practical methods are needed to investigate exchange dynamics between tissue compartments. Some studies on human patient populations have administered gadolinium-based contrast agents (GBCAs) either intrathecally[2–4] or intravenously[5–7] to characterise the time course of compartmental contrast enhancement. Intrathecal GBCA injection reveals the natural exit routes in the brain clearance system, whereas intravenous injection provides information on both entry and exit pathways. Intrathecally-injected GBCA caused enhancement observable on T_1-weighted images within 20 minutes at the base of the skull (foramen magnum), within hours in the cortical sulci and cisternal spaces, and after 24 to 48 hours in brain tissue.[2–4] Intravenously-injected GBCA caused enhancement on T_2-weighted fluid-attenuated inversion recovery (FLAIR) images with a different time course, as leakage into various CSF-filled regions started hours after injection.[5–7] However, these studies were conducted in clinical cohorts and cannot be replicated in non-symptomatic individuals, due to the invasiveness of GBCA injections.[8]

Non-invasive techniques for CSF imaging have also been developed based on the transfer of water or molecular oxygen (O_2) between tissue compartments. CSF production is thought to primarily occur in the cerebral ventricles at the BCSFB through the exchange of water and ions from the blood in the choroid plexuses.[1] To investigate the transfer of water from blood to CSF, one study has used arterial spin labelling with a long labelling duration and post-labelling delay, showing that labelled water reaches CSF from blood within seconds.[9] According to the two traditional models for brain fluid dynamics, namely the Glymphatic System and the Intramural Peri-Arterial Drainage model (IPAD), water influx from the CSF into brain tissue occurs through specialised perivascular spaces and is driven by pulsatility of the arterial wall.[1] To investigate the transfer of water between CSF and brain parenchyma, one study has proposed an inversion-recovery approach with a long echo time (TE)[10] to measure the longitudinal relaxation time (T_1) of CSF, reporting that shorter T_1 in some regions could indicate faster CSF-brain tissue exchange.[10]

Similarly to water, which passes through the BBB and BCSFB facilitated by aquaporin water channels and co-transporters, O_2 can pass through the BBB and the BCSFB due to its lipid solubility and the high vascular permeability of vessels to O_2 (particularly in the choroid plexus and pial vessels) in proximity to CSF.[11] This transport is ultimately driven by the large concentration gradient of O_2 (a difference in oxygen partial pressure, ΔPO_2) from the O_2-rich arterial blood to CSF and tissue, and will depend on the vascular permeability to O_2.[11] Two studies have used custom inversion-recovery sequences to map the T_1 of CSF before and after 100% hyperoxia and thereby map changes in the partial pressure of O_2.[12,13] These studies have shown regional shortening of CSF T_1 upon O_2 breathing and reported hyperoxia-induced effects in the CSF within minutes of O_2 administration, demonstrating the transfer of O_2 from the blood to the CSF compartment.[12,13] However, previous research was limited by its reliance on imaging protocols with relatively large voxel sizes or thick imaging slabs. This limitation was primarily due to the significant specific absorption rates inherent to the employed spin-echo readout techniques.

Here, we aimed to demonstrate non-invasively, with whole-brain coverage and sub-millimetric voxel resolution, the transfer of O_2 between the arterial blood and CSF compartments in a healthy population. To obtain suitable MRI images, we measured T_1 in the CSF using a tailored three-dimensional (3D) Sampling Perfection with Application-optimised Contrasts using different flip angle Evolution (SPACE) pulse sequence with a long TE that effectively suppresses signal from tissues other than CSF given the considerably longer T2 of CSF than other tissues. To obtain information on the rate of O_2 exchange between blood and CSF, we assessed changes in the CSF T_1 during the transition from room air breathing (normoxia) to hyperoxia (100% O_2 administration).

2 Subjects and methods

2.1 Participants

MRI data were acquired in 20 healthy subjects (10/10 males/females, average age ± standard deviation (SD): 34.5 ± 8.8 years, age range: 24-52 years). This study was approved by the Institutional Review Board of the Department of Neurosciences, Imaging and Clinical Sciences, University of Chieti-Pescara (protocol number: 07/2023). All participants provided written informed consent and were instructed to abstain from consuming caffeinated or alcoholic beverages from the night before the experiment. This research was conducted in accordance with the World Medical Association Declaration of Helsinki.

2.2 Experimental protocol

Before undergoing MRI, subjects were fitted with a breathing circuit as described in Tancredi et al[14] for O_2 delivery. The mask was secured to the subject's head using a four-point silicone harness. In the absence of a medical O_2 supply, the circuit provides room air to the participant. When the O_2 supply is switched on, the presence of a reservoir ensures that the inspired O_2 concentration remains consistently close to 100% even when the inspired gas flow during peak inspiration temporarily exceeds the O_2 source supply rate. The air composition inside the mask was monitored through a line connected to a Luer lock sampling port, which directed the samples outside the scanner room to a respiratory gas analyser (ML206, ADInstruments, Dunedin, New Zealand) connected to a PowerLab 16/35 data acquisition and analysis system (PL3516, ADInstruments). Samples were visualised and recorded using LabChart software (v8.1 Pro, ADInstruments). The subject's heartbeat and O_2 saturation levels were continuously monitored using a wireless pulse oximeter (Expression MR200, Philips Healthcare, Best, The Netherlands).

All subjects underwent MRI on a 3 T Prisma system using a 32-channel receive-only head coil (Siemens Healthineers, Forchheim, Germany). At the beginning of the imaging session (Figure 1), structural images were acquired for anatomical reference using an MP2RAGE sequence[15] with the following parameters: sagittal slice orientation, phase encoding direction=anterior-posterior, resolution=1-mm isotropic, field of view (foot-head x anterior-posterior x right-left)=256x256x176 mm^3, repetition time (TR)=5000 ms, TE=3.58 ms, inversion times (TIs)=700/2500 ms, flip angles=4/5 degrees, GRAPPA acceleration factor=3, bandwidth=180 Hz/pixel and acquisition duration=4:59 min:s.

Compared to conventional fast/turbo spin echo, the SPACE readout enables high-resolution 3D spin-echo imaging with a lower specific absorption rate. It uses non-selective, short refocusing pulse trains, alongside flip angles less than 180 degrees for the refocusing radiofrequency pulses. This combination reduces echo spacing while lengthening the usable duration of the spin-echo train and, therefore, the TE.[16] Two versions of the 3D SPACE sequence were implemented, one with an isotropic resolution of 0.9 mm and the other with an isotropic resolution of 3 mm. Both employed a long effective TE to suppress signal from brain tissue compared to CSF.

The high-resolution implementation of the 3D SPACE sequence consisted of two separate acquisitions, where all parameters were kept unchanged except for the TIs, which were set to 3000 ms (TI_1) and 7550 ms (TI_2) to measure T_1. The other parameters were: sagittal slice orientation, phase encoding direction=anterior-posterior, field of view (foot-head x anterior-

posterior x right-left)=230x230x158 mm^3, 0.9-mm isotropic resolution, TR=10010 ms, T_2 preparation time=200 ms, TE=751 ms, turbo factor=599, flip angle=120 degrees, GRAPPA acceleration factor=2, bandwidth=888 Hz/pixel and acquisition duration=7:52 min:s.

The low-resolution 3D SPACE sequence had similar parameters as the high-resolution version, except for the following: resolution=3 mm isotropic, field of view (foot-head x anterior-posterior x right-left)=384x306x216 mm^3, TE=752 ms, flip angle=115 degrees, bandwidth=494 Hz/pixel, and acquisition duration=1:42 min:s.

The high-resolution sequence was employed to calculate T_1 maps at baseline, during room air breathing (normoxia), and at the end of the experiment during 100% O_2 (hyperoxia) (Figure 1). The low-resolution sequence, with the shorter acquisition time, was used to calculate three T_1 maps during the first phase of O_2 administration, providing information on the temporal dynamics of T_1 changes in the CSF caused by hyperoxia. The repeats of each pair of low-resolution acquisitions will be referred to as runs 1, 2 and 3 (Figure 1).

O_2 was administered in two phases of the experiment (Figure 1) with flow at 15 L/min and O_2 humidification for subject comfort. Initially, 100% O_2 was administered for 10 minutes. This duration has been shown to lead to maximum observable change in T_1 of CSF during 100% hyperoxia.[12] The acquisition of three runs enabled the calculation of T_1 maps to investigate dynamic changes in T_1. Then, O_2 administration was paused for approximately 6 minutes and 30 seconds. During this period, a sequence unrelated to the present study was conducted. This pause was inserted to adhere to local safety guidelines regarding 100% O_2 administration. Afterwards, 100% O_2 administration was resumed until the end of the experiment as shown in Figure 1. The effects of hyperoxia on CSF were expected to return to the pre-pause level within the duration of the second acquisition of the high-resolution SPACE TI_1 sequence (Figure 1).[12]

2.3 High-resolution SPACE processing

Image analysis was performed using MATLAB (R2022b, The MathWorks, Natick, MA), the FMRIB software library (FSL) v6.0[17], and the Advanced Normalisation Tools (ANTs) software library.[18] In particular, all rigid image coregistrations were performed using FSL FLIRT[19,20], whereas non-linear coregistrations to standard space were performed using the ANTs SyN function.

To enable the calculation of T_1 maps for both pairs of high-resolution SPACE acquisitions (Figure 1), the TI_2 image was rigidly coregistered to the TI_1 image. Moreover, to ensure image alignment between normoxia and hyperoxia, the high-resolution TI_1 image acquired

during hyperoxia was rigidly coregistered to the high-resolution TI_1 image acquired during normoxia (Figure 1).

A mask of CSF was calculated based on the difference between the TI_2 and TI_1 images acquired during hyperoxia, thereby exploiting the higher signal-to-noise ratio resulting from breathing 100% O_2 compared to breathing room air. To remove any residual tissue signal, the difference between TI_2 and TI_1 was empirically thresholded at 50% of its robust range, that is, the intensity distribution with outlier values removed, and then binarised. MATLAB's *regionprops* function was applied to select the largest connected component from the binary mask. The resulting CSF mask was then rigidly transformed into the space of the high-resolution TI_1 image acquired at normoxia by applying the transformation calculated earlier between TI_1 images at normoxia and hyperoxia.

For both pairs of high-resolution acquisitions (Figure 1), T_1 values were calculated within the CSF mask using qMRLab for Matlab[21] and the *inversion_recovery* routine. The general form of the longitudinal signal recovery model was used, which fits inversion recovery data (S) according to:

$$S(TI) = c\left(1 - 2\exp\left(-\frac{TI}{T_1}\right) + \exp\left(-\frac{TR}{T_1}\right)\right) \#(1)$$

where c is a constant, and the effective TIs were obtained by adding the T_2 preparation time to TI_1 and TI_2.

2.4 Low-resolution SPACE processing

Similar to Section 2.3, to enable T_1 calculation at each run during hyperoxia, each low-resolution TI_2 image was rigidly registered to the corresponding TI_1 image (Figure 1). For each run of the low-resolution sequence, the CSF mask for T_1 mapping was obtained by rigidly aligning the high-resolution TI_1 image acquired during hyperoxia with the low-resolution TI_1 image at each run, and applying the resulting transformation to the CSF mask calculated in Section 2.3. Then, for each run, T_1 values were calculated within the CSF mask according to Equation 1.

2.5 T_1 map alignment and difference image calculation

For visual inspection of T_1 alterations induced by hyperoxia, the high-resolution T_1 maps calculated at hyperoxia and normoxia were rigidly aligned based on the transformation between the respective TI_1 images calculated earlier. Similarly, for visual inspection of the dynamic effect of O_2 inhalation on T_1, all low-resolution T_1 maps were aligned in the space of run 1 by calculating the rigid transformations between the TI_1 images from runs 2 and 3 and

the TI_1 image from run 1, and applying the resulting transformations to the corresponding T_1 maps. Then, difference images were computed between the high-resolution T_1 maps obtained at normoxia and hyperoxia, and between each pair of low-resolution T_1 maps.

2.6 Regional analysis of T_1 values

For regional analysis of T_1 values in the CSF, the following regions of interest (ROIs) were manually delineated using ITK-SNAP within the contours of the high-resolution CSF mask: the anterior lateral ventricles (anterior to the foramen of Monro), the posterior lateral ventricles (posterior to the foramen of Monro, including the body, atrium, occipital and temporal horns of the lateral ventricles), the third ventricle (inferior to the foramen of Monro and superior to the cerebral aqueduct) and the cortical subarachnoid space. These ROIs were selected to enable comparison with previous studies investigating the T_1 values of CSF during hyperoxia[12] and a study suggesting that a faster CSF-tissue exchange rate characterises regions with lower T_1 values.[10] For each subject and all high-resolution and low-resolution T_1 maps, the median T_1 value was calculated in each ROI.

Statistical analyses of the regional median values of T_1 were performed using JASP (v0.19.3.0).[22] All statistical tests were two-tailed, and $p<0.05$ was considered to determine significance.

A two-way repeated-measures ANOVA was performed to test for differences in regional T_1 values over time based on the low-resolution SPACE data acquired during hyperoxia. Two repeated-measures factors were set: time of acquisition (runs 1 to 3) and ROI. To account for potential differences in CSF clearance influenced by the age and sex of the participants,[23,24] age was included as a covariate and sex as a between-subjects factor.

Another two-way repeated-measures ANOVA was performed to test for differences in regional T_1 values over time across normoxia and hyperoxia conditions based on the high-resolution SPACE data. Two repeated-measures factors were set: time of acquisition (normoxia or hyperoxia) and ROI. Similar to the previous test, participant age was included as a covariate and sex as a between-subjects factor.

For both repeated-measures ANOVA tests, assumptions were checked as follows: Mauchly's test evaluated sphericity for factors with more than two levels, Q-Q plots visually assessed normality, and Levene's test evaluated homogeneity of variances. All post hoc analyses were performed using Holm correction to adjust *p*-values for multiple comparisons.

2.7 Analysis in standard space

Higher-level analysis of T_1 differences between normoxia and hyperoxia was performed to identify O_2-induced T_1 shortening at the group level. To this aim, for each subject, both the high-resolution T_1 maps calculated at normoxia and hyperoxia were registered to the 1-mm isotropic Montreal Neurological Institute (MNI) template as follows.

First, the TI_1 image of each SPACE acquisition was rigidly aligned to the structural T_1-weighted MP2RAGE uniform (UNI) image. Compared to conventional T_1-weighted sequences at 3 T, the MP2RAGE UNI image is designed to provide uniform intensity across the scanned volume by correcting for non-T_1 contrast effects, such as receiver field (B_1) inhomogeneity, proton density contrast and transverse decay (T_2*).[15] Moreover, it presents no signal in the CSF, thereby providing a contrast complementary to that observed in the SPACE acquisitions. To enable more accurate registration, strong background noise in air-filled regions was removed from the MP2RAGE UNI image using a MATLAB implementation (*RobustCombination.m* function, https://github.com/JosePMarques/MP2RAGE-related-scripts) of the method proposed by O'Brien and colleagues.[25] This denoised image was used as input for an optimised atlas-based brain extraction algorithm based on ANTs. The extracted brain region was then coregistered to the 1-mm isotropic MNI template using ANTs. The same image transformation was applied to align the individual high-resolution T_1 maps to MNI space.

Using a custom implementation of nearest-neighbour interpolation in MATLAB, each T_1 map in MNI space was downsampled to an isotropic 3-mm resolution. This downsampled voxel size was chosen to reduce the impact of slight misalignment between individual T_1 maps in MNI space and improve the statistical power of group-level analysis. Because the T_1 maps of CSF were sparse in nature, with NaN values assigned to voxels with no CSF signal, the custom implementation of nearest-neighbour interpolation explicitly checked for NaN values at the nearest-neighbour location. If a NaN value was found, the algorithm searched a 3x3x3 neighbourhood for the closest non-NaN value to fill the gap in the downsampled image.

The average T_1 maps at normoxia and hyperoxia were calculated across subjects. To account for data sparsity, the average T_1 value of a voxel was only calculated if the voxel had a value different from NaN in at least 90% of subjects. Otherwise, the average of T_1 in that voxel was set to zero. To assess differences in T_1 of CSF between normoxia and hyperoxia, non-parametric permutation tests were conducted using the *randomise* tool in FSL.[26] Two distinct one-tailed one-sample t-tests were performed to test for $\Delta T_1 > 0$ and $\Delta T_1 < 0$ (where Δ denotes a difference) by providing as input a series of difference images

(one per subject) between the T_1 map calculated at normoxia and the T_1 map calculated at hyperoxia. To maintain the family-wise error rate at 0.05, a threshold of $p<0.025$ was used for each of these two tests (Bonferroni correction). The binary CSF mask for the tests was calculated to include the voxels appearing in both the average T_1 maps at normoxia and hyperoxia. For each test, 5000 permutations were used, along with the bi-dimensional version of threshold-free cluster enhancement, which is designed to correct for multiple comparisons when using sparse images.

3 Results

3.1 Overall CSF appearance on SPACE acquisitions

Figure 2 shows images acquired using the high-resolution SPACE sequence (Figures 2a-b) and the low-resolution SPACE sequence (Figures 2c-d) at the two TIs. Lower windowing was applied to the images at the shorter TI, where CSF was nearly null (Figures 2a and 2c). Notably, residual non-CSF signal appeared only outside the brain, suggesting that the chosen TE effectively minimised signal contributions from brain parenchyma (Figure 2).

3.2 T_1 mapping

Figure 3 shows representative high-resolution T_1 maps acquired at normoxia (Figure 3a) and hyperoxia (Figure 3b). It also shows the difference between these two maps (Figure 3c) and the ROIs used for regional analysis of T_1 (Figure 3d). Compared to breathing room air, O_2 inhalation caused widespread T_1 shortening in the cortical subarachnoid space (Figures 3a-c).

3.3 Regional analysis of T_1

The regional values of T_1 are shown using raincloud plots for both the high-resolution (Figure 5) and low-resolution SPACE acquisitions (Figure 6).

In both repeated measures ANOVA tests, Mauchly's test of sphericity was significant, so the Greenhouse-Geisser correction was applied. The assumptions of normality and variance homogeneity were satisfied.

3.3.1 Regional high-resolution T_1 measurements

There was a significant main effect of ROI on T_1 of CSF, $F(1.893, 32.173)=18.009$, $p<0.001$, $\omega^2=0.250$. Moreover, the effect of hyperoxia on T_1 was ROI-dependent, $F(1.786,$

30.360)=8.646, p=0.001, ω^2=0.034. Finally, there was a marginal between-subjects effect of age on T_1, F(1, 17)=3.811, p=0.068, ω^2=0.072.

The post-hoc tests revealed the following. Overall, there was a significant decrease in T_1 of CSF during hyperoxia compared to normoxia (mean difference=80.2 ms, p<0.001). Moreover, CSF T_1 in the anterior lateral ventricles was significantly higher than in all other ROIs: the posterior lateral ventricles (mean difference=118.0 s, p<0.001), the third ventricle (mean difference=204.6 ms, p<0.001) and the subarachnoid space (mean difference=505.9 ms, p<0.001). CSF T_1 was significantly higher in the posterior lateral ventricles than in both the third ventricle (mean difference=86.6 ms, p<0.001) and cortical subarachnoid space (mean difference=387.8 ms, p<0.001), and CSF T_1 was significantly higher in the third ventricle than in the cortical subarachnoid space (mean difference=301.2 ms, p<0.001). On a regional basis, hyperoxia caused a significant decrease in CSF T_1 in the posterior lateral ventricles (p=0.008, Figure 5b) and, more markedly, in the cortical subarachnoid space (p<0.001, Figure 5d), but not in the other ROIs (Figure 5a and 5c).

3.3.2 Regional low-resolution T_1 measurements

There was a significant main effect of ROI on T_1 of CSF, F(1.910, 32.5)=12.018, p<0.001, ω^2=0.169. The between-subject effect of age on T_1 was also significant, F(1, 17)=6.634, p=0.02, ω^2=0.135. Finally, there was a marginally significant main effect of time on T_1, F(1.601, 27.2)=2.969, p=0.08, ω^2=0.018. While not reaching statistical significance, the p-value=0.08 suggested a trend towards differences in T_1 across runs.

Post-hoc tests using the Holm correction revealed the following. Overall, there was a significant decrease in T_1 of CSF between runs 1 and 3 (mean difference=87.8 ms, p<0.001). Moreover, CSF T_1 in the anterior lateral ventricles was significantly higher than in all other ROIs: the posterior lateral ventricles (mean difference=200.5 ms, p<0.001), the third ventricle (mean difference=267.5 ms, p<0.001) and the subarachnoid space (mean difference=669.2 ms, p<0.001). Similarly, both the posterior lateral ventricles (mean difference=468.7 ms, p<0.001) and the third ventricle (mean difference=401.8 ms, p<0.001) had a significantly higher T_1 than the one measured in the cortical subarachnoid space. Finally, post hoc tests on the interaction between ROI and time revealed that, in the posterior lateral ventricles, T_1 decreased significantly between runs 1 and 3 (mean difference=70.0 ms, p=0.03) and, in the cortical subarachnoid space, T_1 decreased significantly between runs 1 and 2 (mean difference=181.1 ms, p<0.001) and between runs 1 and 3 (mean difference=231.9 ms, p<0.001). On a regional basis, CSF T_1 significantly decreased between runs 1 and 3 in the posterior lateral ventricles (p=0.025, Figure 6b) and between

runs 1 and 2 (p<0.001) and 1 and 3 (p<0.001) in the cortical subarachnoid space (Figure 6d).

3.4 Higher-level analysis of T_1

Figure 7 displays, in MNI space, the across-subject average of the high-resolution T_1 maps of CSF acquired during normoxia (Figure 7a) and hyperoxia (Figure 7b), along with the T_1 difference map between these two conditions (Figure 7c) and the (1 - p) voxel-wise statistical map resulting from the permutation test assessing higher T_1 values at normoxia than hyperoxia (Figure 7d). Results from the permutation test assessing lower T_1 values at normoxia than hyperoxia are not shown, as no significant differences were found. The group-level analysis revealed significant T_1 shortening widespread across the cortical subarachnoid space and, to a lesser degree, in posterior ventricular regions (Figure 7d). T_1 values appeared unchanged in the anterior ventricles (Figure 7d).

4 Discussion

Using a customised whole-brain SPACE MRI protocol, with a long TE to minimise contributions from brain parenchyma, and a hyperoxia protocol, this study examined how 100% O_2 inhalation affects the T_1 of CSF across the whole brain in healthy participants. High-resolution and low-resolution acquisitions, with a long TE, enabled the calculation of 3D T_1 maps of brain CSF, free from signal contamination from surrounding brain tissue. These maps revealed that O_2 inhalation causes widespread T_1 shortening in the cortical subarachnoid space, but not in all ventricular regions over the 10-15 minute timescale of hypoxia studied here. Furthermore, in the cortical subarachnoid space, O_2-induced T_1 shortening of CSF stabilised after approximately 7 minutes of continuous O_2 breathing (Figure 6d).

In the present study, the SPACE sequence[16] was specifically optimised to provide 3D acquisitions with sub-millimetric resolution, making it suitable for studying CSF anatomy. Previous studies on hydrocephalus[27,28] have proposed a similar adaptation of the SPACE protocol to illustrate CSF anatomy, but the present study is the first to propose the SPACE protocol for T_1 mapping in this area. The SPACE sequence was also modified to achieve a faster acquisition time by lowering the image resolution, enabling the observation of time-dependent CSF T_1 changes during hyperoxia. The present application of the SPACE sequence represents a flexible tool that can be adapted in future studies, with a focus on the structural aspects of CSF anatomy or the dynamic changes in CSF longitudinal relaxation time constant. While tested on a Siemens system, protocols from other MRI manufacturers

offer potential for similar modifications: the Volume ISotropic Turbo spin echo Acquisition (VISTA) (Philips Healthcare, Best, The Netherlands) and the CUBE sequence (GE Healthcare, IL, USA).

Having such a protocol readily available on clinical MR systems is timely, given the growing interest in cerebral CSF spaces and CSF circulation.[29] One limitation of the proposed protocol is its long duration for high-resolution T_1 mapping (approximately 15 minutes). However, considering that basic science research is a primary focus of the neurofluids field, we believe that such a long acquisition time in a research setting on healthy subjects is manageable. Future work exploring specific clinical applications of this protocol could refine it for targeted clinical questions within more acceptable examination times.

Regional analysis of T_1 in CSF-containing structures showed that, at baseline, the median T_1 of CSF was systematically longer in the anterior lateral ventricles compared to all other regions (Figure 5, normoxia, and Section 3.3.1). This result agrees with a previous study showing that CSF in the frontal horns of the lateral ventricles has baseline T_1 values significantly longer than in the subarachnoid space. This observation may be caused by the lack of blood-CSF water exchange sites in the anterior ventricles.[10] The presence of such sites elsewhere, specifically the choroid plexuses in the ventricles or pial arteries entering the brain from the subarachnoid space, allows for transfer of water from blood, having a relatively short T_1,[30] to CSF. This mixing effectively shortens the T_1 of CSF relative to areas without blood-CSF water exchange.

In the cortical subarachnoid space, 100% hyperoxia significantly reduced T_1 compared to baseline values (Figure 5d) over a timescale of minutes (Figure 6d). In this ROI, the observed T_1 shortening at our chosen timescale was consistent with previous studies applying a 100% hyperoxic challenge for 15 or 30 minutes.[12,31] Additionally, the rapid hyperoxia-induced T_1 shortening in sulcal CSF was consistent with a study reporting a dynamic signal increase on fast/turbo spin echo images during 5 minutes of 100% hyperoxia.[32] However, previous studies reported no T_1 change in the lateral ventricles during 100% hyperoxia.[12,31,32] Here, instead, T_1 was reduced in the posterior lateral ventricles compared to baseline values (Figure 5b), but the change occurred over a longer timescale than in the cortical subarachnoid space (Figure 6b). Differences in observations across studies might be due to varying definitions of ROIs within the lateral ventricles. One study segmented a region in the anterior horns of the lateral ventricles based on a 20-mm-thick oblique coronal 3D slab,[12] while the others segmented a region across the entire lateral ventricles based on a 91.5-mm-thick transverse 3D slab[31] or a single 7-mm-thick transverse 2D slice.[32] In contrast, the present study subdivided the lateral ventricles into anterior and

posterior, highlighting that T_1 shortening related to 100% hyperoxia only occurs over the timescales studied here in the medial-posterior part of the lateral ventricles, where the choroid plexuses are located. Stable T_1 values in the third ventricle during 100% hyperoxia were consistent with previous results,[12] but seem inconsistent with the anatomy of this region, which contains choroid plexuses along its roof, connected with those in the lateral ventricles through the interventricular foramina (of Monro). The timescale selected in this and earlier studies may have been insufficient to detect T_1 shortening throughout all large-volume CSF compartments.

During 100% hyperoxia, the larger and faster change in T_1 in the cortical subarachnoid space compared to the posterior ventricular regions (Figures 5b, 5d, 6b and 6d) is likely to be related to the nature of blood-CSF exchange sites and the volume of CSF present in each compartment. These two factors are discussed in more detail below.

Around the cortex, O_2 from blood enters the CSF via pial arteries on the brain surface, which are part of a network within the subarachnoid space, a CSF-filled space located between the pia mater and arachnoid mater. Pial arteries have thick walls composed of endothelium, basement membranes and layers of smooth muscle.[33] Because, unlike parenchymal arteries and capillaries, pial arteries are directly adjacent to the CSF, a difference of oxygen partial pressure (ΔPO_2) exists that favours passive outward diffusion of O_2 into CSF. This diffusion, sometimes termed pre-capillary O_2 shunting, allows O_2 to enter the CSF before the blood reaches the capillaries.[34] In the ventricles, O_2 from blood enters the CSF via the choroid plexus, a highly vascularised structure composed of villi, each containing fenestrated capillaries, stromal tissue, and a layer of choroidal epithelial cells interconnected by tight junctions, which form the BCSFB.[35] O_2 dissolved in plasma is expected to diffuse rapidly and freely across these structures.[35,36]

We suggest that a key factor determining the rate and degree of T_1 shortening in a given CSF compartment is the relationship between the permeability surface area product of the local BCSFB and the volume of CSF into which O_2 is transferred. We hypothesise that there is a greater ratio of pial arteries relative to the sulcal CSF volume than there is of choroid plexus vessels relative to ventricular CSF volume, thereby resulting in a faster and greater T_1 shortening in the cortical subarachnoid space during hyperoxia.[31] In ventricular CSF, the dilution of O_2, related to the local volume of CSF, is likely to be slower compared to sulcal CSF. This explanation has also been proposed by studies performed in subjects receiving 100% O_2 under general anaesthesia[37] or through a face mask,[38] which showed signal hyperintensities in subarachnoid CSF much higher than in ventricular CSF on fluid-attenuated inversion recovery MRI.[37,38]

In addition to the number of vessels exchanging O_2, their permeability surface area product will depend on the structure of the vascular walls and thus their permeability. We propose that another factor influencing O_2 transfer from blood into ventricular CSF is O_2 consumption within the BCSFB structure. In pial arteries, O_2 diffuses relatively freely along a steep driving ΔPO_2. In contrast, at the choroid plexus-CSF interface, epithelial cells are highly active in CSF secretion (via ion pumping) and are rich in mitochondria to support this process.[39] We hypothesise that this high metabolic activity makes the epithelium a metabolic sink, rapidly consuming O_2 that diffuses into the stroma. Consequently, the final ΔPO_2 driving O_2 into the bulk ventricular CSF is reduced due to this consumption, making the transfer rate different from that in the pial artery wall. Furthermore, differences in the baseline PO_2 within the ventricles and the sulci, driven in part by the continuous circulation and bulk flow of CSF, may also contribute to the local ΔPO_2 and the effective volume of O_2 distribution.

Based on our observations, we propose that O_2 delivered via hyperoxia may be better suited for investigating exchange between blood and CSF compartments compared to GBCAs. Firstly, O_2 is a simple, rapidly metabolised molecule that avoids the risks of synthetic pharmaceuticals like GBCAs. Secondly, the two compounds differ in their transport mechanisms: O_2 is a small, uncharged, highly lipophilic gas that rapidly traverses endothelial cell lipid membranes via passive diffusion, reflecting transmembrane permeability. GBCAs, conversely, are significantly larger, polar, hydrophilic molecules with a restricted, slower exchange primarily limited by paracellular transport through tight junctions between endothelial cells.[5–7] Therefore, O_2 could probe transmembrane exchange, whereas GBCAs probe the size-exclusion properties of tight junctions. Thus, in the future, T_1 shortening related to the O_2 transfer rate from pial arteries to CSF (or penetrating arteries and the adjacent perivascular spaces or brain tissue) could serve as a marker of the vessel wall's effective permeability to O_2, and by extension, its passive diffusion properties for other small, lipid-soluble molecules. Indeed, we expect the rate of O_2 loss to be proportional to the permeability-surface area product of the vessel wall, which represents its effective "leakiness" to O_2. Thus, for a given ΔPO_2, a higher O_2 transfer rate implies a higher effective O_2 permeability. Factors that alter the physical structure of the arterial wall, such as the number of cell layers, cell junction tightness, or the thickness of the barrier, will affect O_2 movement. Therefore, a change in the O_2 transfer rate could correlate with a change in the passive permeability coefficient for other small, passively diffusing molecules, potentially establishing O_2 diffusion as a new marker of vascular structure in pathologies affecting the vasculature, such as dementia.[40] Notably, measurements of the O_2 transfer rate from pial or penetrating arterioles will only reflect the permeability of the arteriolar wall, which is structurally different from the BBB located at the capillaries.

Potential limitations should be considered when interpreting these results. One factor influencing T_1 shortening in the cortical subarachnoid space compared to the ventricles could be partial voluming with the surrounding brain parenchyma, which is T_1-insensitive to hyperoxia,[31] and may dilute hyperoxia-induced T_1 changes in CSF. However, this was addressed by using an extralong TE value to suppress signals from the brain parenchyma around CSF-containing structures (Figure 2), making it unlikely that partial voluming significantly affected the measured T_1. Furthermore, the influence of hyperoxia on CSF hydrodynamics warrants consideration. Although the effects of normobaric 100% hyperoxia on CSF dynamics in healthy controls have not been investigated, in traumatic brain injury patients, short-term (2 hours) normobaric 100% hyperoxia significantly increased local brain tissue oxygenation without affecting intracranial pressure, cerebral perfusion pressure, or mean arterial pressure.[41] Thus, our sub-30-minute hyperoxia exposure was unlikely to affect CSF dynamics. Notably, subjects were imaged supine, which enhances CSF flow compared to upright positions.[42,43] Consequently, the observed T_1 shortening during hyperoxia mainly applies to the supine position used in high-field MRI.

To conclude, this study applied a 3D sequence for imaging CSF and measuring CSF T_1 across the entire brain, adapting a protocol available on clinical MR systems. Experiments conducted with 100% hyperoxia demonstrated that O_2 induces T_1 shortening effects in the CSF, these occurring more rapidly in the subarachnoid space than in the ventricles. This finding is consistent with the passive diffusion of O_2 across the high density of blood-CSF exchange sites around the cortex. The methodology presented could help characterise CSF structures and assess vascular permeability to O_2, serving as a marker of cerebrovascular health.

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6 Author contribution statement

Emma Biondetti: conceptualisation, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, visualisation, writing (original draft).

Davide Di Censo: data curation, formal analysis, investigation, methodology, software, writing (reviewing & editing).

Sara Pomante: investigation, writing (reviewing & editing).

Stefano Censi: investigation, methodology, writing (reviewing & editing).

Ekaterina Bliakharskaia: investigation, writing (reviewing & editing).

Manuela Carriero: writing (reviewing & editing).

Francesca Graziano: investigation, writing (reviewing & editing).

Alessandra Stella Caporale: methodology, writing (reviewing & editing).

Antonio Maria Chiarelli: funding acquisition, methodology, writing (reviewing & editing).

Richard Geoffrey Wise: funding acquisition, methodology, project administration, resources, supervision, writing (reviewing & editing).

7 Statements and declarations

7.1 Ethical considerations

This study was approved by the Institutional Review Board of the Department of Neurosciences, Imaging and Clinical Sciences, University of Chieti-Pescara (Comitato di Revisione della Ricerca sull'Essere Umano – CReREU, protocol number: 07/2023) on the 16th February 2024. This research was conducted ethically, in accordance with the World Medical Association Declaration of Helsinki.

7.2 Consent to participate

All participants provided written informed consent before enrolment in the study.

7.3 Consent for publication

All participants provided written informed consent to publish the results from this study.

7.4 Declaration of conflicting interest

Manuela Carriero received research support from Siemens Healthineers (Forchheim, Germany).

7.5 Funding statements

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7.6 Data availability

The anonymised and defaced MR acquisitions supporting the findings from this study are available in this open repository: https://doi.org/10.5281/zenodo.17672757.

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9 Figure legends

Figure 1. Experimental protocol. The diagram shows the time allocated for the sequences in this study. The region shaded in light blue corresponds to 100% O_2 administration. The open time slots during the experiment were allocated for imaging unrelated to the present study. The labels' run 1', 'run 2' and 'run 3' denote the three pairs of low-resolution SPACE acquisitions performed during the first phase of O_2 administration.

Figure 2. Representative SPACE acquisitions. For a representative subject, the same sagittal, coronal and transverse slices are shown for the high-resolution SPACE acquisition acquired at normoxia at TI_1 (a) and TI_2 (b). Similar slices are shown for the first run of the low-resolution SPACE acquisition at TI_1 (c) and TI_2 (d). The slices depicted in (c) and (d) were cropped to match the field of view of those in (a) and (b).

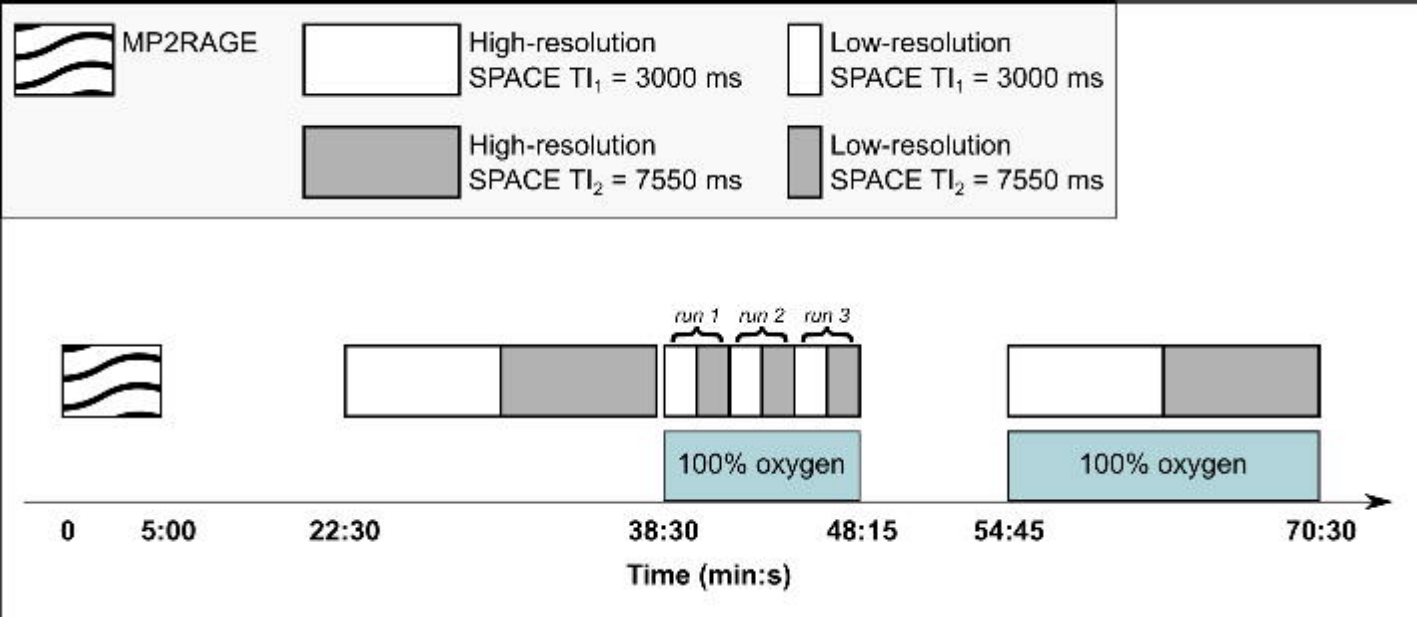
Figure 3. High-resolution T_1 maps. For the same representative subject as in Figure 2, the same sagittal, coronal and transverse slices are shown for the T_1 maps acquired during normoxia (a), hyperoxia (b) and the difference between the two (c). The maps in panels a-c are overlaid on the high-resolution SPACE image acquired at TI_2. The ROIs used for regional analysis of T_1 values in the CSF are shown in (d) overlaid on the high-resolution SPACE image acquired at TI_2 during hyperoxia.

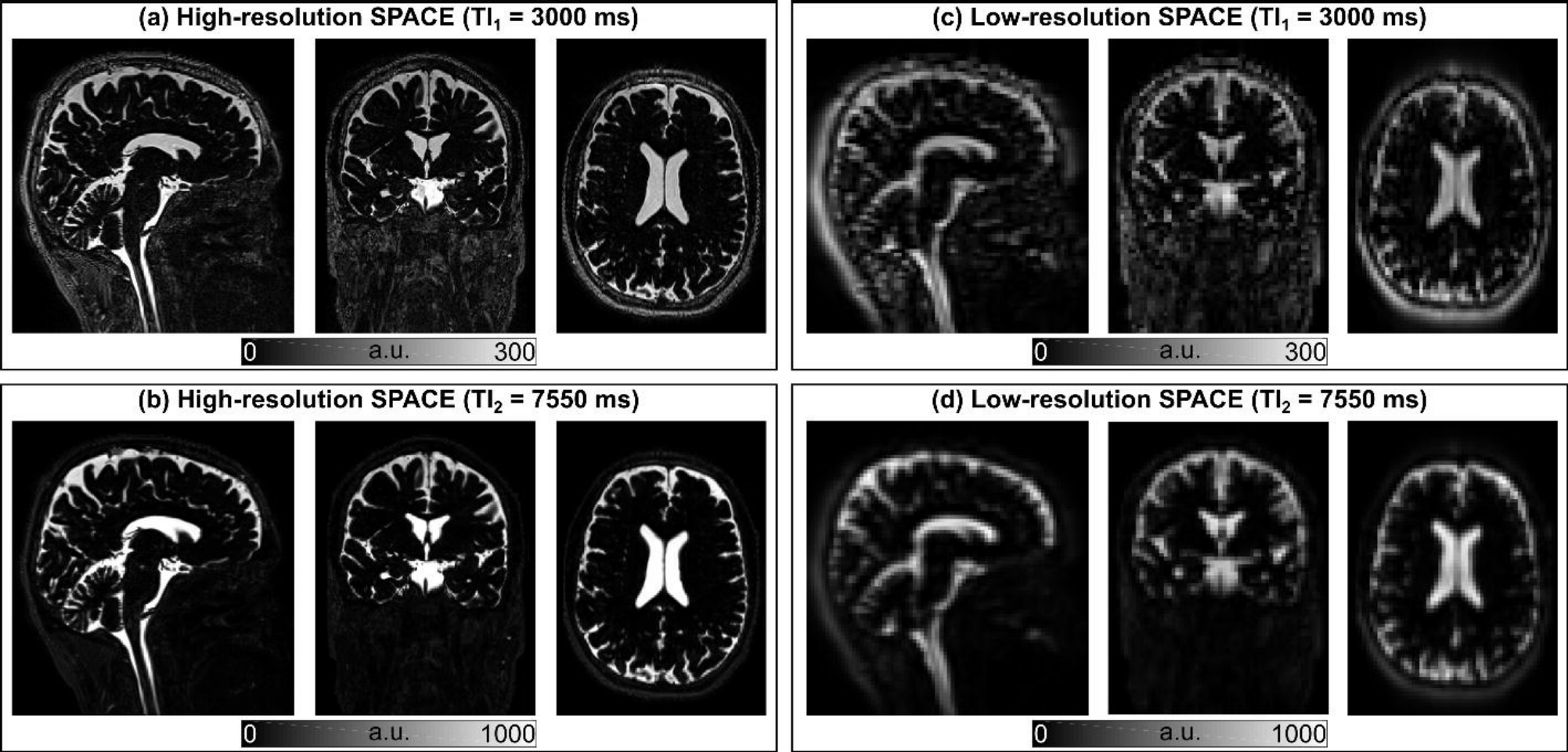
Figure 4. Low-resolution T_1 maps. For the same representative subject as in Figure 2, the same sagittal, coronal and transverse slices are shown for the T_1 maps acquired during hyperoxia at run 1 (a), run 2 (b), and run 3 (c). T_1 difference maps between each pair of runs are shown in (d-f).

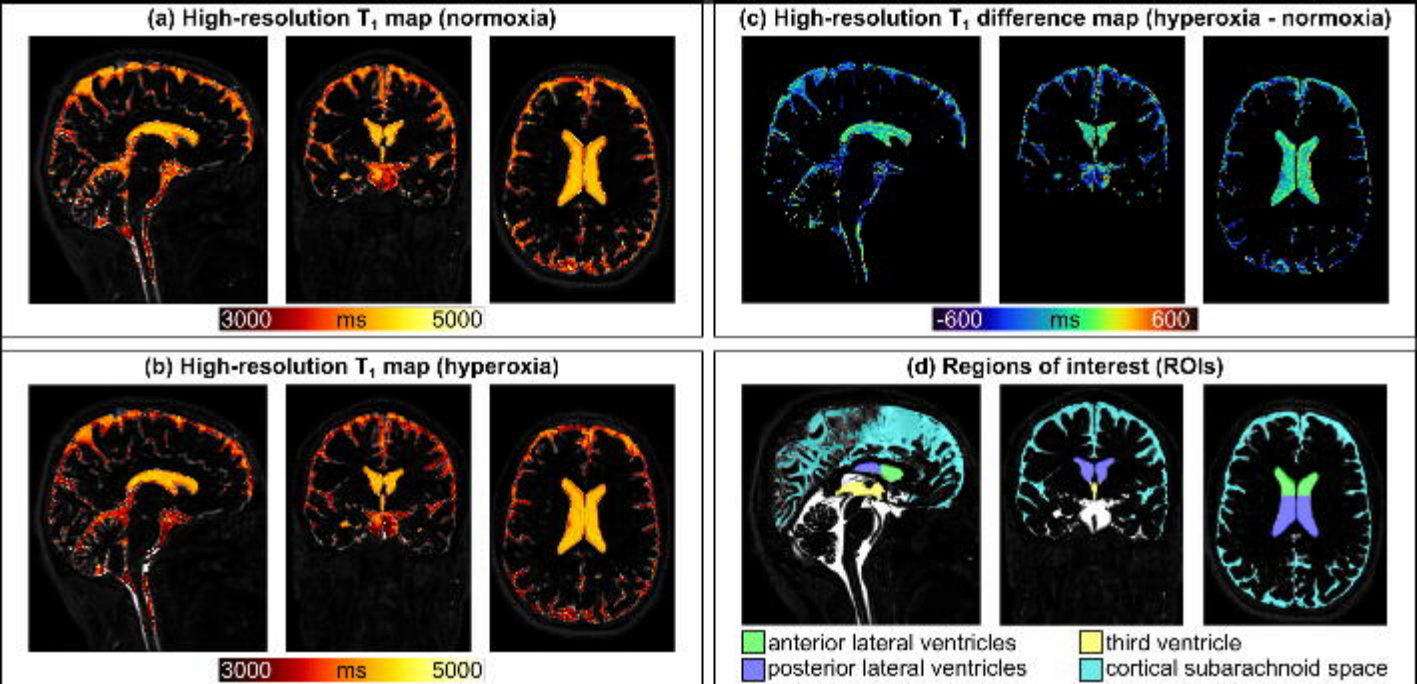
Figure 5. Raincloud plots of regional high-resolution T_1 measurements. For each ROI, the individual subject median values of T_1 measured during normoxia and hyperoxia are shown using a raincloud plot. This plot includes, for each experimental condition, a scatter plot of individual data points, a box plot, and a histogram. In the scatter plots for each region, pairs of data points connected by a line indicate measurements from the same subject under the two experimental conditions. Significant differences between the two experimental conditions are denoted as ** $p<0.01$, *** $p<0.001$.

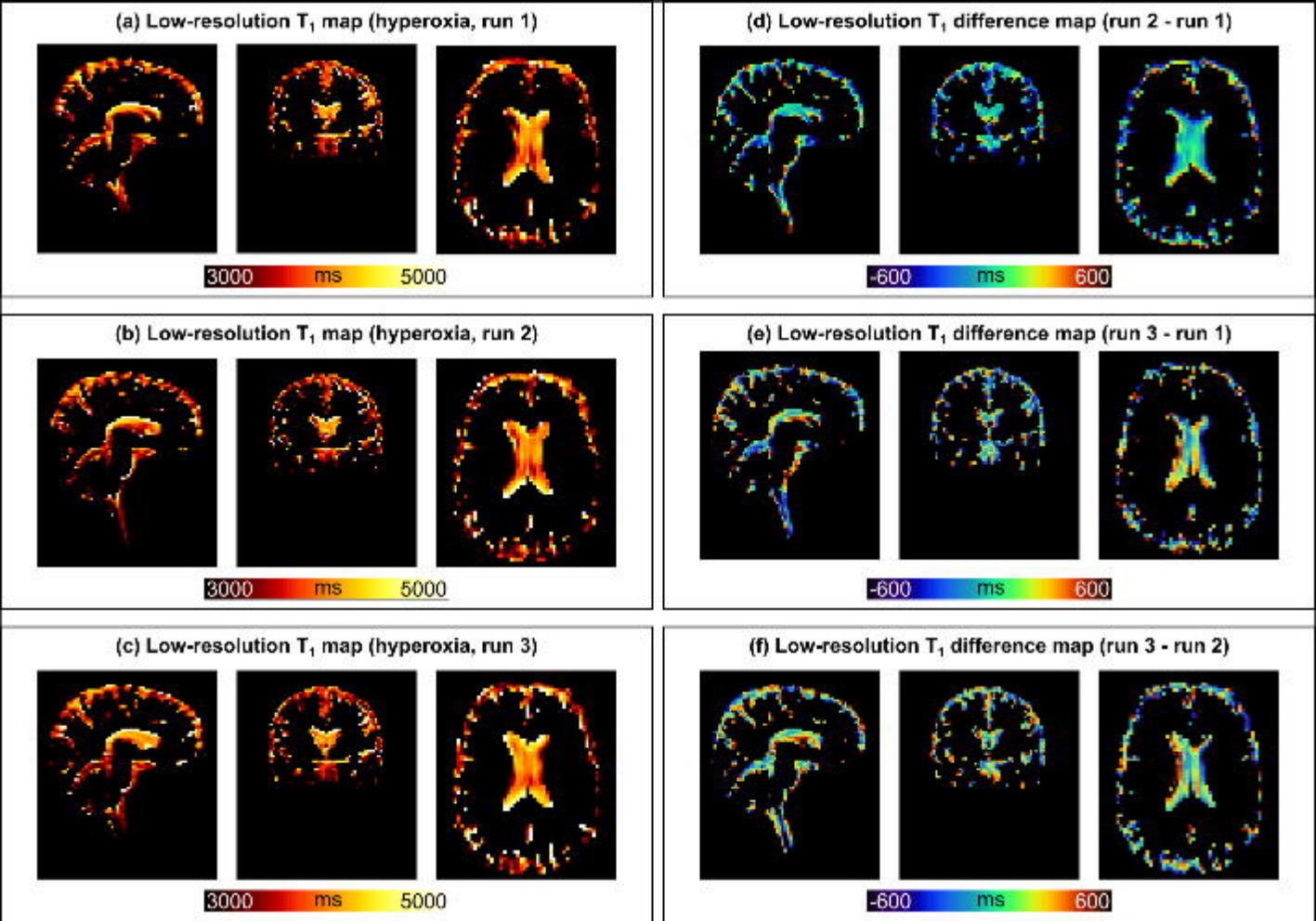
Figure 6. Raincloud plots of regional low-resolution T_1 measurements. For each ROI, the individual median values of T_1 measured at three time points (runs 1, 2 and 3) during hyperoxia are shown using a raincloud plot. This plot includes, for each run, a scatter plot of individual data points, a box plot, and a histogram. In the scatter plots for each region, triplets of data points connected by a line indicate measurements from the same subject taken at each time point. Significant differences between the three time points are denoted as * $p<0.05$, *** $p<0.001$.

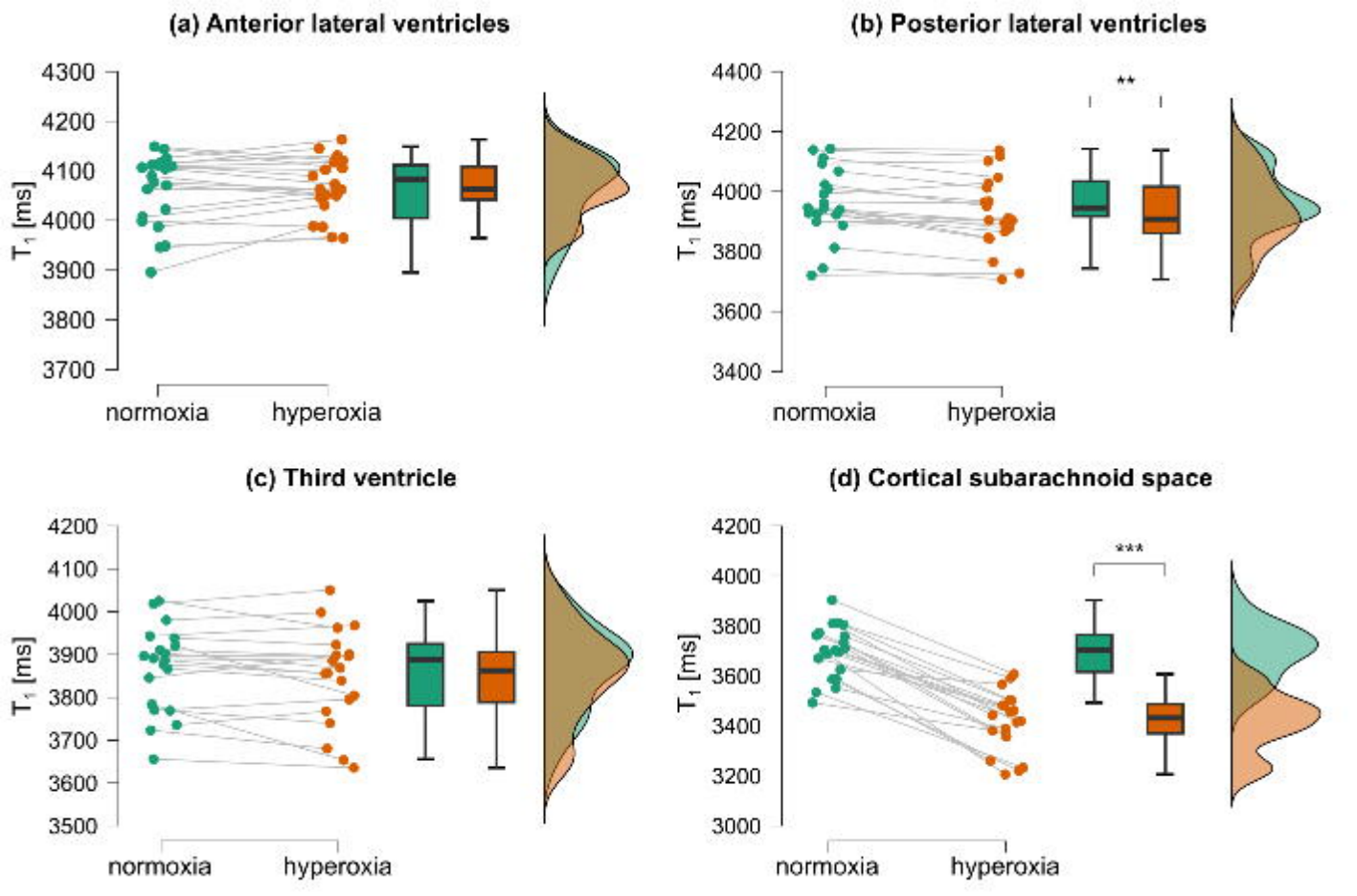
Figure 7. Average T_1 maps in MNI space. The same sagittal, coronal and transverse slices are shown for the average T_1 maps in MNI space acquired during normoxia (a), hyperoxia (b) and the difference between the two (c). The results of the non-parametric permutation test comparing higher T_1 at normoxia than hyperoxia are shown in (d). All maps are shown overlaid on the 1-mm isotropic T_1-weighted MNI template.

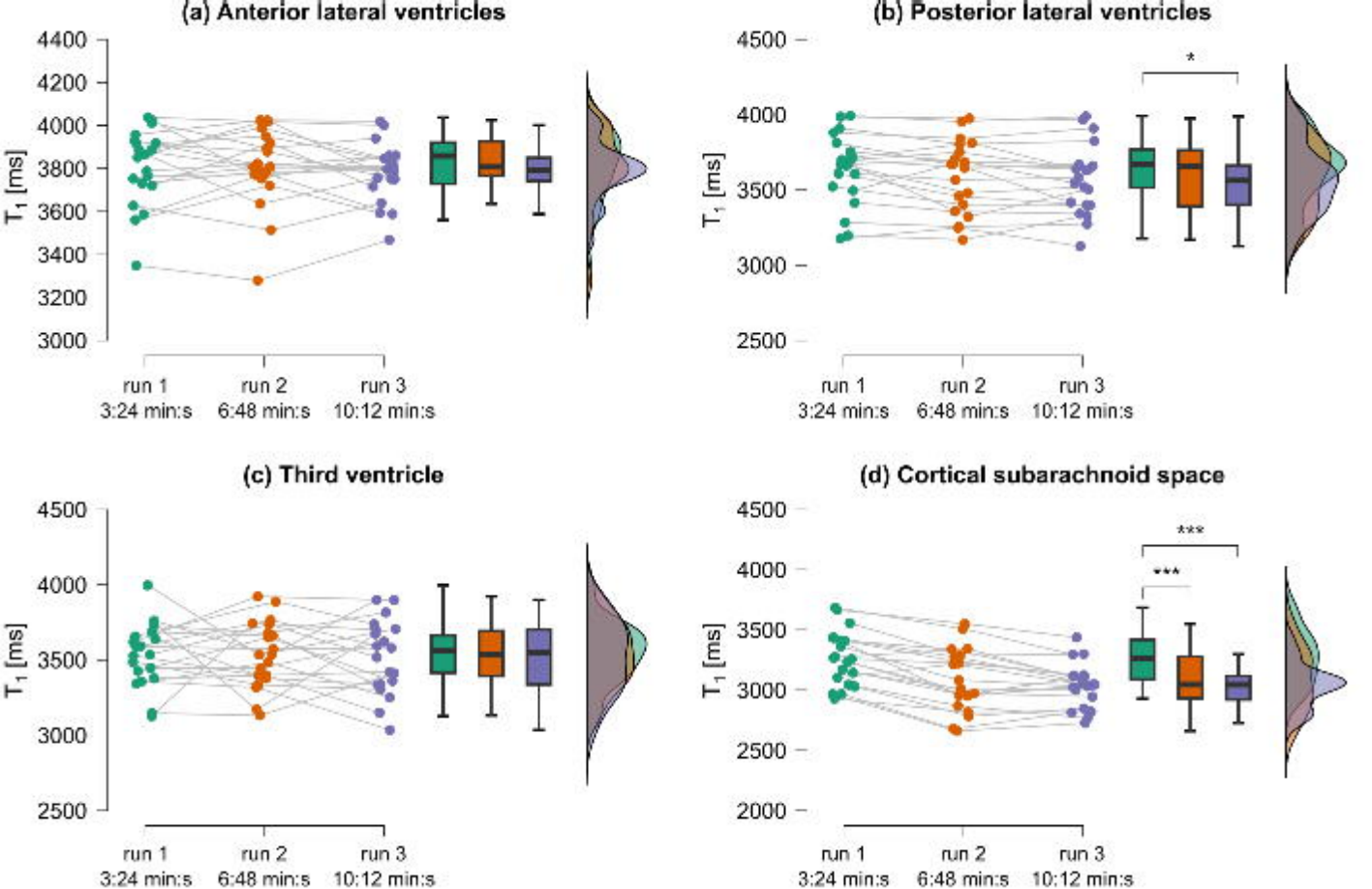

MP2RAGE
High-resolution SPACE TI1 = 3000 ms
Low-resolution SPACE TI1 = 3000 ms
High-resolution SPACE TI2 = 7550 ms
Low-resolution SPACE TI2 = 7550 ms
run 1
run 2
run 3
100% oxygen
100% oxygen
0
5:00
22:30
38:30
48:15
54:45
70:30
Time (min:s)

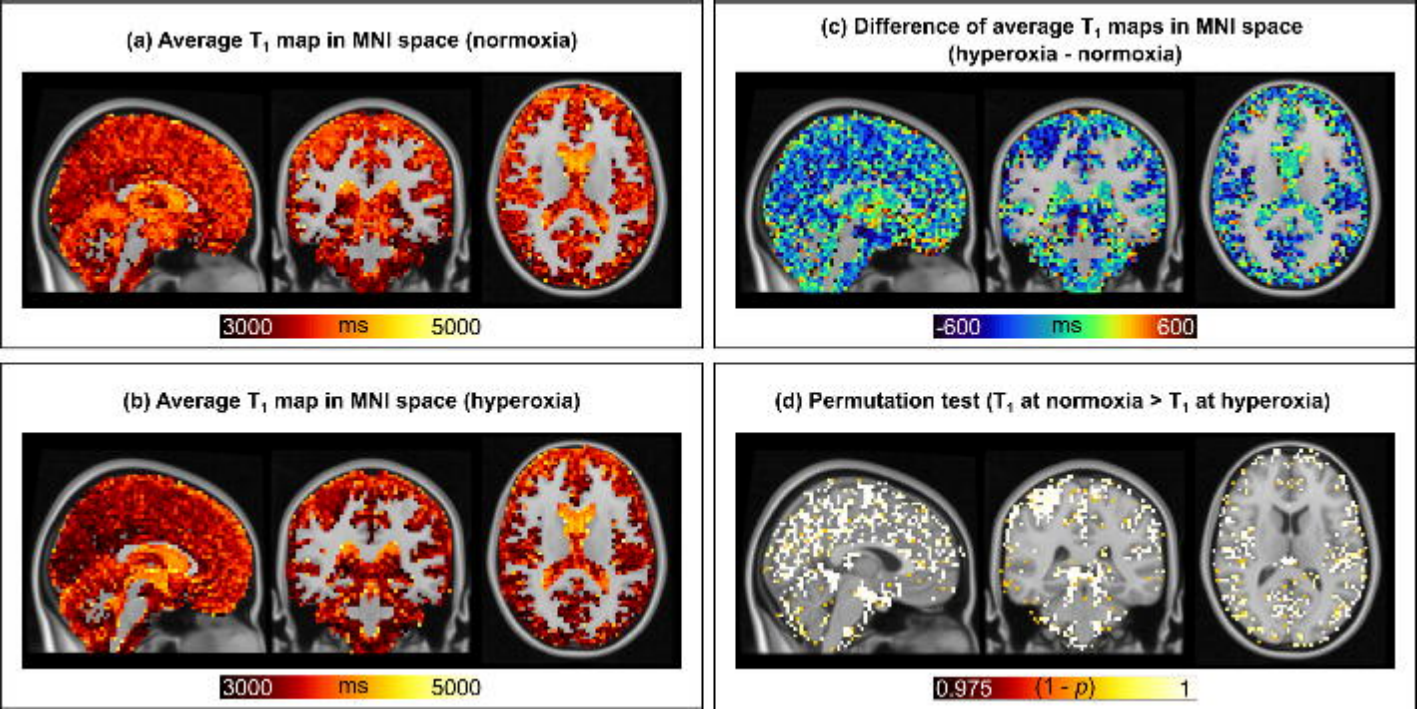

(a) High-resolution SPACE (TI1 = 3000 ms)
0
a.u.
300
(c) Low-resolution SPACE (TI1 = 3000 ms)
0
a.u.
300
(b) High-resolution SPACE (TI2 = 7550 ms)
0
a.u.
1000
(d) Low-resolution SPACE (TI2 = 7550 ms)
0
a.u.
1000


(a) High-resolution T_1 map (normoxia)
3000 ms 5000
(c) High-resolution T_1 difference map (hyperoxia - normoxia)
-600 ms 600
(b) High-resolution T_1 map (hyperoxia)
3000 ms 5000
(d) Regions of interest (ROIs)
anterior lateral ventricles
posterior lateral ventricles
third ventricle
cortical subarachnoid space


(a) Low-resolution T1 map (hyperoxia, run 1)
3000 ms 5000
(b) Low-resolution T1 map (hyperoxia, run 2)
3000 ms 5000
(c) Low-resolution T1 map (hyperoxia, run 3)
3000 ms 5000
(d) Low-resolution T1 difference map (run 2 - run 1)
-600 ms 600
(e) Low-resolution T1 difference map (run 3 - run 1)
-600 ms 600
(f) Low-resolution T1 difference map (run 3 - run 2)
-600 ms 600


(a) Anterior lateral ventricles
4300
4200
4100
4000
3900
3800
3700
T1 [ms]
normoxia
hyperoxia
(b) Posterior lateral ventricles
**
4400
4200
4000
3800
3600
3400
T1 [ms]
normoxia
hyperoxia
(c) Third ventricle
4200
4100
4000
3900
3800
3700
3600
3500
T1 [ms]
normoxia
hyperoxia
(d) Cortical subarachnoid space
***
4200
4000
3800
3600
3400
3200
3000
T1 [ms]
normoxia
hyperoxia


(a) Anterior lateral ventricles
(b) Posterior lateral ventricles
(c) Third ventricle
(d) Cortical subarachnoid space
T1 [ms]
run 1
3:24 min:s
run 2
6:48 min:s
run 3
10:12 min:s
*
***
***


(a) Average T_1 map in MNI space (normoxia)
3000 ms 5000
(c) Difference of average T_1 maps in MNI space (hyperoxia - normoxia)
-600 ms 600
(b) Average T_1 map in MNI space (hyperoxia)
3000 ms 5000
(d) Permutation test (T_1 at normoxia > T_1 at hyperoxia)
0.975 (1 - p) 1