**T1 Relaxation Time is Prolonged in Healthy Aging: a Whole Brain Study**

**ABSTRACT**

**Background/Aim:** Measurement of tissue characteristics such as the longitudinal relaxation time (T1) provides complementary information to the volumetric and surface based structural analyses. We aimed to investigate T1 relaxation time characteristics in healthy aging via an exploratory design in the whole brain. The data processing pipeline was designed to minimize errors related to aging effects such as atrophy.

**Materials andmethods:** 60 healthy participants underwent MRI scanning (28 F, 32 M, age range: 18-78, 30 young and 30 old). T1 relaxation times of the entire brain were mapped by using an ROI based method on 134 brain areas in young and old populations.

**Results:** Age-related T1prolongation was observed in various subcortical (bilateral hippocampus, caudate and thalamus)and cortical brain structures(bilateral Precentral Gyrus, bilateral Middle Frontal Gyrus, bilateral Supplementary Motor area (SMA), left Middle Occipital Gyrus, bilateral Postcentral Gyrus bilateral and bilateral Heschl’s Gyrus) as well as cerebellar regions(GM regions of Cerebellum: Bilateral Cerebellum III, cerebellum IV V, Cerebellum X, Cerebellar Vermis u 4 5, Cerebellar Vermis u 9 and WM Cerebellar regions: left Cerebellum IX, bilateral Cerebellum X and Cerebellar Vermis u 4 5).

**Conclusion:** T1mapping provides a practical quantitative MRI (qMRI) methodology for studying the tissue characteristics in healthy aging. T1values are significantly increased in the aging group among half of the studied ROIs (57 ROIs out of 134).

**Keywords:** T1mapping; healthy aging; brain; qMRI

# Introduction

According to the 2019 Revision of the World Population Prospects, by 2050,people over the age of 65 will be 16% of the total population[1]. Sucha change in the pattern of population growth in favor of elderly people emphasizes the importance of aging studies in neuroimaging. During healthy aging, functional[2] and structural[3] changes occur in the brain. Beyond healthy aging, a notable amount of the aging population is susceptible to neurodegenerative diseases. The most common of them is Alzheimer’s disease, which affectsapproximately 30% of people aged 85 or older[4]. Understanding healthy brain aging is therefore crucial to be able to detect the early biomarkers of the age-related diseases.

Age-related structural brain changes including cortical thickness and signal intensity were reported in various areas [5]. These changes are so profound that age prediction from brain MR images can feasibly be performed with machine learning[6]or based on the contrast at the tissue borders[7]. On the other hand, there are also age-related changes in the brain in intrinsic characteristics of the tissues. It is demonstrated that the main driver of the age-related GM volume loss in subcortical areas is the tissue property changes rather than atrophy[8].In several studies, myelin, water content and iron were reported as the main factors that contribute to the structural changes in the aging brain. In MR imaging, these differences are observed through longitudinal relaxation time T1,the longitudinal relaxation rate R1 (R1 =1/T1) and transverse relaxation time T2. However, due to several technical limitations, the MRI signal bears inadequate information regarding the microstructure of the underlying tissues[16] through the T1, R1 and T2 measures. First, the signal is a nonlinear mix of several signal contrasts (T1, T2 or proton density (PD)). Second, choice of the data acquisition parameters such as inversion time, echo time, flip angle, can only be determined sub-optimally. Third, hardware artefacts in conventional MRI are difficult to circumvent through reverse engineering the signal. Due to these factors, use of conventional MRI techniques does not allow prediction of underlying properties of the human brain tissue. On the other hand, T1 relaxation time is a good indicator of local tissue density (such as water content), macromolecules(e.g. myelin), paramagnetic concentration (e.g. iron), as well as the lipid and protein compositions of the underlying tissue. Another superior property of the T1 is that it is less affected by hardware artefacts[17].Additionally, T1 of the human brain has also been reported as a biomarker of development and maturation[18]. The above-mentioned properties emphasize that T1 is a suitable parameter to investigate aging changes.

The studies that address quantification of T1 in the whole brain are scarce. In healthy aging, the studies that performed T1 mapping can be grouped based on the subject populations. Most of the studies conducted in this area are cross-sectional designs. Steen et al. [19]examined age-related T1changes in 18‐72 years old 55 healthy volunteers and reported that T1 increased with age in the genu, frontal white matter, occipital white matter, putamen, and thalamus. Contrary to the subcortical areas, significant decrease in T1 with age was observed in cortical gray matter[19]. In a comprehensive study of 115 healthy subjects aged 4 to 72, it was reported that T1 exhibits a quadratic pattern in such a way that it begins decreasing in adolescence and reaches to minimum in 40-60 years but then starts to increasing [20].Another study with 56 normal volunteers with ages 11-71 years reported a positive linear relationship between T1 and age in the genu of the corpus callosum (CC) and frontal WM regions and a negative linear relationship in the left substantia nigra (SN)[21]. In line with the outcomes of Cho et al. (1997), the quadratic patterns were also shown in 3 fronto-parietal WM regions and the right SN in this study[22].In a recent study on 70 healthy subjects aged 20–76, a significant increase T1 in thalamus and WM but a decrease in amygdala, nucleus accumbens and the ventral-inferior putamen were reported [23]. Another recent study of 211 healthy participants aged 20–89 years found that there was negative linear relationship between T1 and age in putamen, thalamus and head of the caudate nucleus, but positive linear correlation in frontal lobe WM, globus pallidus and genu of the CC[24].In all of these cross-sectional studies, the age range of the participants in the cohort seem to be a major confoundingfactor prohibiting comparison of the findings.

Despitethe abundance of the cross-sectional studies, there are only two longitudinal designs investigating age-related changes of T1.In a part of the LBC1936 longitudinal study (Wave 2: N=653, mean age =73; Wave 3: N=442, mean age=76) hippocampal T1 was demonstrated to significantly decrease across waves[25]. In the other longitudinal study(7-year period,17 healthy subjects, 51–77 years), an age related decrease of mean T1 in GM cortex and unchanged mean T1 in WM were reported[26]. As seen from the literature, there is no consistency in the reported T1 changes during aging and it seems that the limited number of ROIs targeted in these studies prohibit a general comparison across the findings.

In this study, we aimed to conduct an exploratory approach tounderstand T1 relaxation time differences in aging by studying the entire brain. The data processing pipeline was designed to minimize theerrors related to aging effects such as atrophy. It is well known that age-related GM-WM loss and also brain atrophy become prominent after 70-80 years of life[27]. The age range of the old group participated in our study was chosen specifically to circumvent this problem.

# Methods

## Participants

A total of 63 participants volunteered to participate in the study, however 1 youngand 2 old subjects were excluded from the study because of their claustrophobia.Hence, a total of 60; 30 young (Mean=26.36, SD=2.69, 12 F, 18 M) and 30 old(Mean=67.46, SD=4.89, 16 F, 14 M) subjects participated in the study. Demographic information of the remaining 30 participants is given in Table 1. Classification of the participants into age groups was conducted according to the aging criterion of the United Nations [28].

The recruiting of the participants was conducted via distributed fliers, social media and with the help of our circle of acquaintances.All the participants signed informed consent according to the principles of the Declaration of Helsinki and the study was approved by the Institutional Review Board of ??? (acikca yazalim hangi universite oldugunu). Exclusion criteria were history of a neuropsychological/psychiatric disorder, alcoholism, use of medication affecting the central nervous system (CNS) and cognitive decline in the aging group. None of the participants reported having a neuropsychological/psychiatric disorder or suffering from alcoholism and all of them stated that they were not using any medication affecting CNS. In addition, the participants included in the study did not have any physical disability preventing the application of the cognitive tests (visual, hearing, etc.), nora metal prosthesis or pacemaker, and claustrophobia which would endanger their MR scanning.To determine whether the older participants were cognitively healthy, Standardized Mini Mental State Examination (SMMSE)[29] and Geriatric Depression Scale[30] were administered. The cut-off scores were 25 and 11, respectively. All participants fulfilled these criteria, as indicated in Table 1.

*Table 1. The demographical information of the subjects.*

|  |  |  |
| --- | --- | --- |
|  | Old | Young |
| Age (Mean ± SD) | 67.46±.4.89 | 26.36±.2.69 |
| Gender | Female=16Male=14 | Female=12Male=18 |
|

|  |
| --- |
| SMMSE (Mean ± SD) |

 | 26.34 ± 0.46 | - |
| GDS (Mean ± SD) | 5.28 ± 0.84  | - |

## Procedure

Structural MRI data were collectedat the UMRAM MRCenter, Bilkent University on a 3 Tesla Siemens MR scanner.The scan time was 20 minutes. High resolution 3D anatomical brain images were collected with MPRAGE protocol (TR=2500 ms, TE=3.16 ms, Bandwidth=199 Hz/Pixel, matrix 256\*256, Slice Thickness 1mm, 256 slices, FOV=256\*256 (axial), Number of Averages=1). Then 4 brain images with four different flip angles (3˚, 5˚, 15˚, 30˚) that adhered to the same imaging coordinates with the MPRAGE sequence were collected with FLASH sequence (TR=20ms, TE=4.15 ms, Bandwidth=199 Hz/Pixel, matrix 256\*256, with Slice Thickness 3 mm, 44 slices, FOV=256\*256 (axial), Number of Averages=1).MPRAGE and FLASH sequences were preferred because MPRAGE yields high resolution images with low specific absorption rate (SAR) even in high magnetic field MRIs, and FLASH sequence introduces images varied contrast images in short scanning times. Moreover, these sequences are widely available in various scanners.

## Data Processing

### Preprocessing

Data collection is prone to head motion due to the long scan time. To remove head motion, images were deobliqued using AFNI’s 3dWarp program [31].In addition, skull removal and bias field correction was performed with FAST tool [32]. For standardization, the images were aligned to the standard stereotaxic space (TLRC) by auto\_tlrc program of AFNI [31].

### T1 Mapping

It was previously reported that Variable Flip Angle (VFA) provides a better alternative to conventional methods through improved precision and speed[33]. Hence, we used VFA with 4 different flip angles (FA)for mapping the spin lattice relaxation time (T1) of each voxel. FLASH is an appropriate sequence providing opportunity to collect images at different contrasts[34], allowing enhancement of data through different flip angles. For this purpose, we collected four FLASH images with varying flip angles (3˚, 5˚, 15˚, 30˚).

Eq. 1 demonstrates the intensity value I(x,y,z) of the voxel at (x,y,z) coordinates acquired with FLASH sequence. The intensity is calculated by tissue characteristics such as magnetization transfer constant (M0), longitudinal relaxation time (T1), transverse relaxation time (T2) and scanning parameters such as repetition time (TR), echo time (TE) and flip angle (α).

$Iα(x,y,z)=\frac{M0(x,y,z) e^{-TE/T\_{2}\*}sin(α)(1-e^{-TR/T\_{1}}))}{(1-cos(α) e^{-TR/T\_{1}})}$ (1)

Based on the requirement of VFA method, we collected four images with different flip angles. For really small flip angles (e.g. α=3˚) cos(α) approaches to 1, so the equation (1) is reduced to Eq. 2 [35]:

$Iα(x,y,z)=M0(x,y,z) e^{-TE/T\_{2}\*}sin(α)$ (2)

In this way, the intensity value of the FLASH image collected with 3˚ flip angle is described as a constant c=M0(x, y, z)$e^{-TE/T\_{2}\*}$sin (3˚). Hence, equation 1 can berewritten as follows:

$Iα(x,y,z)=\frac{c(sin(α)/sin(3)) (1-e^{-TR/T\_{1}}))}{(1-cos(α) e^{-TR/T\_{1}})}$ (3)

Iα (x, y, z) in equation (3) represents the intensity value observed in FLASH images acquired with 5˚, 15˚ and 30˚ flip angles, respectively, where c is acquired from the image with α =3˚. So far, all the parameters in Eq. (3) are known except for T1. The usage of 3 equations derived from 3 images and the only one unknown parameter (T1) make this problem over-determined. Based on previous studies, the range of the T1 is determined as 0-4000 ms. For all these candidate values of T1, intensity Iα(x,y,z) is calculated for all three images (α=5˚, 15˚ and 30˚) based on eq. (3). Then, computed theoretical Iα for each T1 and measured real Iα in image is subtracted and squared for the voxel (x,y,z). Through a least square error fit, the T1 value of the Iα which has the smallest error is assigned as the T1 value of that particular voxel.This method is implemented in MATLAB[36]to create 3D T1 maps of each participant.

### Segmentation

FSL’s FAST tool[32] is used to segment the MPRAGE image, into three tissue types (WM, GM and CSF). The MPRAGE image is aligned to the T1 map image through the FLASH images. Hence, the binary CSF mask produced from the MPRAGE image can be used to remove the CSF from the T1 maps, to take care of the data processing errors due to the atrophy in the cortex and ventricular enlargementin the subcortical areas of the aging group. Thebinary masks of WM and GM produced from the MPRAGE are then used as a basis for T1 measurements in specific ROIs depicted by the atlas (see Fig. 1). The usage of WM masks is especially important to minimize the partial volume effects (PVE) in the aging brain. These procedures are illustrated in Figure 1.



**Figure 1. Data processing pipeline for T1 mapping(Red: bilateral caudate and putamen ROIs from the atlas).**

### ROI Analyses

AFNI’s CA\_N27\_ML atlas is used for ROI signal measurements. We have created ROIs based on this atlas and measured average T1 values of each participant on a total of 134 regions: 12 regions from subcortical area, 72 regions for cortex and 50 regions in cerebellum (25 for each GM and WM area). Additionally, 72 WM masks in cortex are created for elimination of WM tissues surrounding gyri.

### Statistical Analyses

Kolmogorov-Smirnov test is applied for T1 values of each ROI to determine the distribution of the data. Then, according to the outcome either independent samples t-test or Mann-Whitney U Test is conducted to investigate the T1 variations of the defined ROIs between young and old participants. The outcomes are interpreted for Bonferroni corrected p values suitable for 2 repeated measures, one from each hemisphere. The false positive rate is controlled using family-wise error (FWE) correction for multiple comparisons, and thresholded at *p*<0.05 at the cluster level.

# Results

## Subcortical Area

A Kolmogorov-Smirnov test indicated that T1 values in this region had a normal distribution *(p≥.05)*. Independent Samples t-test demonstrated that average T1 value in bilateral hippocampus, caudate and thalamus of the old group were significantly higher than those of younger counterparts.Fig. 2.a. shows the average T1 values that significantly increased in the aged group.

**a.**

**b.**

**Figure 2. Average T1 values measured in subcortical area (a), cerebellum GM (b), cerebellum WM (c) and cortex (d).**

**(R: Right; L: Left; u: unilateral;Hipp: Hippocampus; Ca: Caudate;Thal: Thalamus; Cereb: Cerebellum/Cerebellar; Pre-CG: Precentral Gyrus;MFG: Middle Frontal Gyrus;SMA: Supplementary Motor Area; MOG: Middle Occipital Gyrus;Post-CG: Postcentral Gyrus; HG: Heschl’s Gyrus)**

* 1. **Cerebellum**

Kolmogorov-Smirnov testindicated that the T1 values in GM regions of the cerebellum were not normally distributed *(p≤.05)*. A Mann-Whitney U test indicated significant age-related differences in average T1 measurements in 9 GM regions of the cerebellum. The average T1 values of old participants measured in bilateral Cerebellum III, Cerebellum IV V, Cerebellum X, Cerebellar Vermis u 4 5 and Cerebellar Vermis u 9 were significantly greater than those of the young group as seen in Fig 2.b. Similarly, a Kolmogorov-Smirnov test indicated that T1 values measured in WM regions in the cerebellum did not have a normal distribution *(p ≤ .05)*. The results of the Mann-Whitney U Test showed that the average T1 value measured in left Cerebellum IX, bilateral Cerebellum X and Cerebellar Vermis u 4 5 of the old participants were significantly higher than those of young participants (Fig. 2.c.).

## Cortex

A Kolmogorov-Smirnov test demonstrated that T1 values in this area violated the normality assumption *(p ≤ .05)*. According to the Mann-Whitney U test, age-related significant increase in average T1 values were reported in 38 ROIs including bilateral Precentral Gyrus, bilateral Middle Frontal Gyrus, bilateral Supplementary Motor area (SMA), left Middle Occipital Gyrus, bilateral Postcentral Gyrus bilateral and bilateral Heschl’s Gyrus. The average T1 values measured in these ROIs are given in Fig. 2.c.

Overall, we have demonstrated that there is a trend indicating that average T1 values measured in the brain significantly prolonged with increasing age. We did not observe a significant reduction of T1 in any of the ROIs.

# Discussion& Conclusion

Quantitative MRItechniques with different contrast mechanisms are used in the clinic to provide valuable information about both normal and pathological brain tissues. with each other

Previous studies reported differences of T1 in subcortical and cortical areas of patients with Parkinson’s[37]and Alzheimer’s disease [38]. These outcomes indicate the potential of T1 mapping in neurodegenerative disease research.Determination of T1 variation in thebrain is also important from a cytoarchitectural point of view. It wasshown that R1 maps of the visual cortex and retinotopic maps are associated with many visual area borders[39].

In our study, T1 values in the whole brain of young and old participants were measured based on 134 ROIs from the CA\_N27\_ML atlas. (In this study,T1 maps of the whole brainwere created including 218 ROIs defined in the TT\_N27 atlas.??? Intro’dan cikarttigim satirda baska atlas ve sayi yaziyor) This allowed us to investigate T1 changes during healthy aging comprehensively.To the best of our knowledge, this is the first study investigating age-related changes of T1 relaxation time in the ROIs selected from the whole brain using an exploratory approach. The major finding of this study is that, age-related T1 prolongation is observed in various subcortical and cortical brain structures, as well as cerebellar regions.More specifically, in a cohort of young (18-35 years old) and early aging (60-78 years old) groups, age-related prolongation of T1 in several subcortical, cortical, and cerebellar areas (57 of 134 ROIs) is observed.All of the significant changes observed in this study are related to prolongation of T1. We did not observe a significant decrease in T1 in any of the ROIs between these two age groups.

In terms of *subcortical structures:*We observed significant T1 increases in bilateral caudate, thalamus and hippocampus in the older group relative to younger participants.The findings of our study in these subcortical areas replicated the outcomes of some previous studies indicating an age-related T1 increase in basal ganglia[40] and thalamus[19,23,24] in elderly. A possible origin of increased T1 in subcortical regions in our experiment might be explained by the concomitant loss of myelin in these structures.Age-related demyelination in thalamus[41]and in basal ganglia[42] have been previously reported.Althoughincreased iron content in elderly shortens T1,a degeneration of the myelin sheets has been observed in elderly due to iron accumulation[43]. Water content also influences T1 and it is strongly correlated with iron in several regions including caudate and thalamus[13]. Unfortunately, the underlying region specific mechanism of the association among iron, myelin and T1 is poorly understood[13,42]. Therefore, further studies with complementary techniques (such as MR spectroscopy) and multiparameter approaches investigating myelin water fraction (MWF) are needed to unveil the individual aging mechanisms.

Our outcomes contradict with some recent studies which reported a decreased T1[23]and no change[44]in deep GM structures (e.g. basal ganglia) of old participants. This conflict might stem from the difference between the ROI measurements in these studies and ours. For instance, in one of these studies, manual drawing of the ROIs on a single mid-slice on the population-averaged map was used[23].In our study 134 3D ROIs are created for each participant’sMR image by registering to the stereotaxic space and atlas. We developed an automated data processing pipeline free from biases stemming from subjective measurements. Therefore, the discrepancy between our results and others’ may be attributed to the choices in such quantification techniques. In the other study[44]presenting conflicting outcomes with ours, T1 was measured on an ROI which was a combination of several subcortical structures (e.g. caudate, putamen, thalamus etc.). Such combination of structures might cause losing regionally-specific information which is important in aging[45].Finally, the CSF T1 values are prominently different than those of GM and WM areas, deserving special treatment. We removed the CSF areas in subcortical and cortical regions to minimize the effect of age-related atrophy and ventricular enlargements on tissue concentrations and to measure T1 more precisely. We believe that some portion of the reduction of T1 reported in other studies might result from confounding factors that were not accommodated during the initial data processing steps.

In terms of *cortical structures:*Our findings of elongated T1are in line with some studies on somatosensory cortex (PCG)[46]and on occipital gyrus[47].On the other hand, a decrease in T1 with aging[19,44,48,49]or no change in cortex[50]were reported in other works.The difference between the age range of the participants in Gracien et al.’s study(2017) and ours possibly presents the main source of this contradiction (i.e. 55-71 years in the former, 18-78 years in the latter). Earlier, it has been reported that the T1 differences may follow a quadratic pattern[20].Gracien’s study(2017) might be focusing on the decreasing range of this pattern while our study focuses on the increasing range. Global T1 measurements based on frequency distributions (or spectra) were conducted in two studies[48,49]. In these studies, the aging effect was reported as decreased T1 in GM and increased T1 in WM. These studies did not distinguish the T1changes with respect to ROI. Hence, a comparison between these studies and ours is impossible.

In terms of*cerebellum*, we found T1 prolongation in several structures including cerebellum III, X, and vermis. There are very few studies investigating T1 changes in aging in the cerebellar area. The sheet-like structure of cerebellum is composed of complex cellular layers which are really thin (≤ 1mm)[51]. Moreover, the myelination degree[52] varies in different cortical depths, also cell sizes, distribution and densities across the cerebellar lobes[53]. Perhaps the complexity of the cerebellar anatomy is a prohibiting factor in ROI based analysis of T1 changes in cerebellum. We have replicated outcomes of Saito (2009) reporting an increase in WM anterior sub-segment of cerebellum. On another front, one recent study by Badve et al. (2015) reported that age-related changes were non-existing in cerebellum and cerebellar vermis[21]. In Badve and colleagues’ study, quantitative metrics were measured with Magnetic Resonance Fingerprinting (MRF) technique, in which slice thickness was greater than that in our study. Resolution differences might have been effective in the conflicting outcomes between their results and ours.

Although there are abundant previous studies focusing on subcortical structures, the literature is not rich in evaluating the T1 variation in cortex and cerebellum. The complex and folded topology of cortex and cerebellum is a possible reason of the absence ofqMRI and microstructural studies in these areas. There are several limitations imposed by the aging process and complexity of the automatic processing of brain images. The cortical thinning[5] is a crucial factor that would introduce PVE and worsens interpretation of the cortical data which already has a complex structure.

The present study has several limitations that should be addressed.The variable flip angle method which we have used in the present study is reported to overestimate T1 values in vivo due to imperfect spoiling and B1 bias[54]. Although the correction methods for flip angle inhomogeneities were proposed previously[55], many qMRI studies -including ours- lack a correction while computing the T1 maps. Only after flip angle corrections are done on individual brains, the T1 evaluation methods would indicate accurate changes between age groups. It is important to identify within which range flip angle inhomogeneities are tolerated to predict T1 maps.To test the restrictions of our study, we ran simulations to compute the range of errors in predicting the T1 values. We can safely state that our results are valid, if the variability of flip angles remain in the range of ±10 % in comparison to the settings of the MR protocol (results available upon request).

This study has a cross-sectional design which limits the interpretation individual aging patterns. Longitudinal studies should be conducted in the future to provide a better understanding of the age-related changes and minimize inter-subject variations. To sum up, our report of increased T1 characteristics in healthy aging is centered on young and old adults and limits the generalization to ages outside this age range.

Furthermore, the interpretation of T1 measurements is affected by other factors such as the initial atlas registration and regional boundaries of the anatomical structures.Another limitation worthy to note is the method of registration. There are two different age groups whose anatomical properties differ a lot. We have created special masks for each participant to remove CSF for a better differentiation of WM and GM. This way, at least we were able to remove the age-dependent increase in ventricles and the effects of atrophy. Age-specific atlases may be used for future studies. In addition, when we consider biological variation introduced by the regional heterogeneity of the aging patterns, the complexity of predicting MR signal characteristics represented by T1 should be considered carefully.

# REFERENCES

[1] United Nations. World Population Prospects 2019: Highlights | Multimedia Library - United Nations Department of Economic and Social Affairs 2019. https://www.un.org/development/desa/publications/world-population-prospects-2019-highlights.html (accessed March 9, 2021).

[2] Pergher V, Demaerel P, Soenen O, Saarela C, Tournoy J, Schoenmakers B, et al. Identifying brain changes related to cognitive aging using VBM and visual rating scales. NeuroImage Clin 2019;22. https://doi.org/10.1016/j.nicl.2019.101697.

[3] Erickson KI, Miller DL, Roecklein KA. The aging hippocampus: Interactions between exercise, depression, and BDNF. Neuroscientist 2012:82–97. https://doi.org/10.1177/1073858410397054.

[4] Pichla M, Bartosz G, Sadowska-Bartosz I. The Antiaggregative and Antiamyloidogenic Properties of Nanoparticles: A Promising Tool for the Treatment and Diagnostics of Neurodegenerative Diseases. Oxid Med Cell Longev 2020. https://doi.org/10.1155/2020/3534570.

[5] Salat DH, Lee SY, van der Kouwe AJ, Greve DN, Fischl B, Rosas HD. Age-associated alterations in cortical gray and white matter signal intensity and gray to white matter contrast. Neuroimage 2009;48 (1):21–8. https://doi.org/10.1016/j.neuroimage.2009.06.074.

[6] Varikuti DP, Genon S, Sotiras A, Schwender H, Hoffstaedter F, Patil KR, et al. Evaluation of non-negative matrix factorization of grey matter in age prediction. Neuroimage 2018;173:394–410. https://doi.org/10.1016/j.neuroimage.2018.03.007.

[7] Lewis JD, Evans AC, Tohka J. T1 white/gray contrast as a predictor of chronological age, and an index of cognitive performance. Neuroimage 2018;173:341–50. https://doi.org/10.1016/j.neuroimage.2018.02.050.

[8] Lorio S, Lutti A, Kherif F, Ruef A, Dukart J, Chowdhury R, et al. Disentangling in vivo the effects of iron content and atrophy on the ageing human brain. Neuroimage 2014;103:280–9. https://doi.org/10.1016/j.neuroimage.2014.09.044.

[9] Geyer S, Weiss M, Reimann K, Lohmann G, Turner R. Microstructural parcellation of the human cerebral cortex &ndash; from Brodmann&rsquo;s post-mortem map to in vivo mapping with high-field magnetic resonance imaging. Front Hum Neurosci 2011. https://doi.org/10.3389/fnhum.2011.00019.

[10] Stüber C, Morawski M, Schäfer A, Labadie C, Wähnert M, Leuze C, et al. Myelin and iron concentration in the human brain: A quantitative study of MRI contrast. Neuroimage 2014;93:95–106. https://doi.org/10.1016/j.neuroimage.2014.02.026.

[11] Lutti A, Dick F, Sereno MI, Weiskopf N. Using high-resolution quantitative mapping of R1 as an index of cortical myelination. Neuroimage 2014;93:176–88. https://doi.org/10.1016/j.neuroimage.2013.06.005.

[12] Rooney WD, Johnson G, Li X, Cohen ER, Kim SG, Ugurbil K, et al. Magnetic field and tissue dependencies of human brain longitudinal 1H2O relaxation in vivo. Magn Reson Med 2007;57:308–18. https://doi.org/10.1002/mrm.21122.

[13] Gelman N, Ewing JR, Gorell JM, Spickler EM, Solomon EG. Interregional variation of longitudinal relaxation rates in human brain at 3.0 T: Relation to estimated iron and water contents. Magn Reson Med 2001;45:71–9. https://doi.org/10.1002/1522-2594(200101)45:1<71::AID-MRM1011>3.0.CO;2-2.

[14] Ogg RJ, Steen RG. Age-related changes in brain T1 are correlated with iron concentration. Magn Reson Med 1998;40:749–53. https://doi.org/10.1002/mrm.1910400516.

[15] Neeb H, Zilles K, Shah NJ. Fully-automated detection of cerebral water content changes: Study of age- and gender-related H2O patterns with quantitative MRI. Neuroimage 2006;29:910–22. https://doi.org/10.1016/j.neuroimage.2005.08.062.

[16] Tofts PS, Steens SCA, Cercignani M, Admiraal-Behloul F, Hofman PAM, Van Osch MJP, et al. Sources of variation in multi-centre brain MTR histogram studies: Body-coil transmission eliminates inter-centre differences. Magn Reson Mater Physics, Biol Med 2006;19:209–22. https://doi.org/10.1007/s10334-006-0049-8.

[17] Deoni SCL. Quantitative relaxometry of the brain. Top Magn Reson Imaging 2010;21:101. https://doi.org/10.1097/RMR.0b013e31821e56d8.

[18] Wahlund LO, Agartz I, Almqvist O, Basun H, Forssell L, Saaf J, et al. The brain in healthy aged individuals: MR imaging. Radiology 1990;174:675–9.

[19] Steen RG, Gronemeyer SA, Taylor JS. Age‐related changes in proton T1 values of normal human brain. J Magn Reson Imaging 1995;5:43–8. https://doi.org/10.1002/jmri.1880050111.

[20] Cho S, Jones D, Reddick WE, Ogg RJ, Grant Steen R. Establishing norms for age-related changes in proton T1 of human brain tissue in vivo. Magn Reson Imaging 1997;15:123–6.

[21] Badve C, Yu A, Rogers M, Ma D, Liu Y, Schluchter M, et al. Simultaneous T1 and T2 Brain Relaxometry in Asymptomatic Volunteers Using Magnetic Resonance Fingerprinting. Tomography 2015;1:136–44. https://doi.org/10.18383/j.tom.2015.00166.

[22] Badve C, Yu A, Rogers M, Ma D, Sunshine J, Gulani V, et al. Regional brain T1 and T2 relaxometry in healthy volunteers using magnetic resonance fingerprinting. Proc Intl Soc Mag Reson Med 23 2015;1:0121.

[23] Okubo G, Okada T, Yamamoto A, Fushimi Y, Okada T, Murata K, et al. Relationship between aging and T1 relaxation time in deep gray matter: A voxel-based analysis. J Magn Reson Imaging 2017;46:724–31. https://doi.org/10.1002/jmri.25590.

[24] Kupeli A, Kocak M, Goktepeli M, Karavas E, Danisan G. Role of T1 mapping to evaluate brain aging in a healthy population. Clin Imaging 2020;59:56–60. https://doi.org/10.1016/j.clinimag.2019.09.005.

[25] Anblagan D, Valdés Hernández MC, Ritchie SJ, Aribisala BS, Royle NA, Hamilton IF, et al. Coupled changes in hippocampal structure and cognitive ability in later life. Brain Behav 2018;8:e00838. https://doi.org/10.1002/brb3.838.

[26] Deichmann R, Hilker-Roggendorf R, Steinmetz H, Reitz SC, Gracien R-M, Klein JC, et al. Evaluation of brain ageing: a quantitative longitudinal MRI study over 7 years. Eur Radiol 2016;27:1568–76. https://doi.org/10.1007/s00330-016-4485-1.

[27] Courchesne E, Chisum HJ, Townsend J, Cowles A, Covington J, Egaas B, et al. Normal Brain Development and Aging: Quantitative Analysis at in Vivo MR Imaging in Healthy Volunteers. Radiology 2000;216:672–82. https://doi.org/10.1148/radiology.216.3.r00au37672.

[28] Unidas. O de N. The World Population Prospects: The 2017 Revision. World Popul. Prospect. 2017 Revis., 2017. https://doi.org/10.1017/CBO9781107415324.004.

[29] Güngen C, Ertan T, Eker E. Standardize Mini Mental Test’in Geçerlik ve Güvenilirliği. Türk Psikiyatr Derg 2002;13:273–81.

[30] Ertan T, Eker E. Reliability, validity, and factor structure of the geriatric depression scale in Turkish elderly: Are there different factor structures for different cultures? Int Psychogeriatrics 2000;12:163. https://doi.org/10.1017/S1041610200006293.

[31] Cox RW. AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. Comput Biomed Res 1996;29:162–73. https://doi.org/10.1006/cbmr.1996.0014.

[32] Zhang Y, Brady M, Smith S. Segmentation of brain MR images through a hidden Markov random field model and the expectation-maximization algorithm. IEEE Trans Med Imaging 2001;20:45–57. https://doi.org/10.1109/42.906424.

[33] Deoni SCL, Peters TM, Rutt BK. High-resolution T1 and T2 mapping of the brain in a clinically acceptable time with DESPOT1 and DESPOT2. Magn Reson Med 2005;53:237–41. https://doi.org/10.1002/mrm.20314.

[34] Fischl B, Salat DH, Van Der Kouwe AJW, Makris N, Ségonne F, Quinn BT, et al. Sequence-independent segmentation of magnetic resonance images. Neuroimage, vol. 23, 2004, p. S69–84. https://doi.org/10.1016/j.neuroimage.2004.07.016.

[35] Buxton RB. Introduction to Functional Magnetic Resonance Imaging. vol. 19. 2009. https://doi.org/10.1097/00041327-200406000-00017.

[36] The Mathworks Inc. MATLAB - MathWorks. WwwMathworksCom/Products/Matlab 2017. https://doi.org/2016-11-26.

[37] Nürnberger L, Gracien RM, Hok P, Hof SM, Rüb U, Steinmetz H, et al. Longitudinal changes of cortical microstructure in Parkinson’s disease assessed with T1 relaxometry. NeuroImage Clin 2017;13:405–14. https://doi.org/10.1016/j.nicl.2016.12.025.

[38] Su L, M. Blamire A, Watson R, He J, Aribisala B, T. O’Brien J. Cortical and Subcortical Changes in Alzheimer’s Disease: A Longitudinal and Quantitative MRI Study. Curr Alzheimer Res 2016;13:534–44. https://doi.org/10.2174/1567205013666151116141416.

[39] Sereno MI, Lutti A, Weiskopf N, Dick F. Mapping the human cortical surface by combining quantitative T1 with retinotopy. Cereb Cortex 2013;23:2261–8. https://doi.org/10.1093/cercor/bhs213.

[40] Keuken MC, Bazin PL, Backhouse K, Beekhuizen S, Himmer L, Kandola A, et al. Effects of aging on T1 , T2∗ , and QSM MRI values in the subcortex. Brain Struct Funct 2017;222:2487–505. https://doi.org/10.1007/s00429-016-1352-4.

[41] Callaghan MF, Freund P, Draganski B, Anderson E, Cappelletti M, Chowdhury R, et al. Widespread age-related differences in the human brain microstructure revealed by quantitative magnetic resonance imaging. Neurobiol Aging 2014. https://doi.org/10.1016/j.neurobiolaging.2014.02.008.

[42] Steiger TK, Weiskopf N, Bunzeck N. Iron Level and Myelin Content in the Ventral Striatum Predict Memory Performance in the Aging Brain. J Neurosci 2016;36:3552–8. https://doi.org/10.1523/jneurosci.3617-15.2016.

[43] Peters A. The effects of normal aging on myelin and nerve fibers: A review. J Neurocytol 2002:581–93. https://doi.org/10.1023/A:1025731309829.

[44] Gracien RM, Nürnberger L, Hok P, Hof SM, Reitz SC, Rüb U, et al. Evaluation of brain ageing: a quantitative longitudinal MRI study over 7 years. Eur Radiol 2017. https://doi.org/10.1007/s00330-016-4485-1.

[45] Allen JS, Bruss J, Brown CK, Damasio H. Normal neuroanatomical variation due to age: The major lobes and a parcellation of the temporal region. Neurobiol Aging 2005;26:1245–60. https://doi.org/10.1016/J.NEUROBIOLAGING.2005.05.023.

[46] Salat DH, Fischl B, van der Kouwe AJW, Clarke RJ, Segonne F, Corkin S, et al. Age-related changes in T1 relaxation times across the surface of the cortex. 8th Int. Conf. Funct. Mapp. Hum. Brain. Sendai, Japan Neuroimage, 2002.

[47] Erramuzpe A, Schurr R, Yeatman JD, Gotlib IH, Sacchet MD, Travis KE, et al. A Comparison of Quantitative R1 and Cortical Thickness in Identifying Age, Lifespan Dynamics, and Disease States of the Human Cortex. Cereb Cortex 2021;31:1211–26. https://doi.org/10.1093/cercor/bhaa288.

[48] Suzuki S, Sakai O, Jara H. Combined volumetric T1, T2 and secular-T2 quantitative MRI of the brain: age-related global changes (preliminary results). Magn Reson Imaging 2006;24:877–87. https://doi.org/10.1016/j.mri.2006.04.011.

[49] Saito N, Sakai O, Ozonoff A, Jara H. Relaxo-volumetric multispectral quantitative magnetic resonance imaging of the brain over the human lifespan: global and regional aging patterns. Magn Reson Imaging 2009;27:895–906. https://doi.org/10.1016/j.mri.2009.05.006.

[50] Papadopoulos K, Tozer DJ, Fisniku L, Altmann DR, Davies G, Rashid W, et al. T I-relaxation time changes over five years in relapsing-remitting multiple sclerosis. Mult Scler 2010. https://doi.org/10.1177/1352458509359924.

[51] Van Essen DC, Donahue CJ, Glasser MF. Development and evolution of cerebral and cerebellar cortex. Brain. Behav. Evol., 2018, p. 158–69. https://doi.org/10.1159/000489943.

[52] Wyatt KD, Tanapat P, Wang SSH. Speed limits in the cerebellum: Constraints from myelinated and unmyelinated parallel fibers. Eur J Neurosci 2005;21:2285–90. https://doi.org/10.1111/j.1460-9568.2005.04053.x.

[53] Müller U, Heinsen H. Regional differences in the ultrastructure of Purkinje cells of the rat. Cell Tissue Res 1984;235:91–8. https://doi.org/10.1007/BF00213728.

[54] Stikov N, Campbell JSW, Stroh T, Lavelée M, Frey S, Novek J, et al. In vivo histology of the myelin g-ratio with magnetic resonance imaging. Neuroimage 2015;118. https://doi.org/10.1016/j.neuroimage.2015.05.023.

[55] Helms G, Dathe H, Dechent P. Quantitative FLASH MRI at 3T using a rational approximation of the Ernst equation. Magn Reson Med An Off J Int Soc Magn Reson Med 2008;59:667–72. https://doi.org/10.1002/mrm.21542.