Current Research in MRI

Original Article

Comparison of Volume Measurements on Magnetic Resonance Imaging and Cadaveric Sections of the Lentiform Nucleus and Its Importance in Functional Neurosurgery Procedures

Selim Kayacı[1], Fatma Beyazal Çeliker[2], Orhan Baş[3], Semih Diyarbakır[4], Mehmet Faik Özveren[5]

[1]Department of Neurosurgery, Erzincan Binali Yıldırım University, Faculty of Medicine, Erzincan, Turkey
[2]Department of Radiology, Recep Tayyip Erdoğan University, Faculty of Medicine, Rize, Turkey
[3]Department of Anatomy, Samsun University, Faculty of Medicine, Samsun, Turkey
[4]Department of Anatomy, Erzincan Binali Yıldırım University, Faculty of Medicine, Erzincan, Turkey
[5]Department of Neurosurgery, Anadolu Hospital, Kütahya, Turkey

Cite this article as: Kayacı S, Beyazal Çeliker F, Baş O, Diyarbakır S, Özveren MF. Comparison of volume measurements on magnetic resonance imaging and cadaveric sections of the lentiform nucleus and its importance in the functional neurosurgery procedures. *Current Research in MRI* 2023;2(3):41-49.

Corresponding author: Selim Kayacı, e-mail: selim_kayaci@hotmail.com

Received: July 24, 2023 **Accepted:** September 03, 2023 **Publication Date:** October 10, 2023

DOI:10.5152/CurrResMRI.2023.23066

ABSTRACT

Objective: Functional neurosurgery is one of the fastest-growing areas of neurosurgery. However, complications are encountered that are not negligible during the operations. In this study, we measure and compare the volume of the lentiform nucleus using magnetic resonance imaging (MRI) and anatomical sections.

Methods: Thirteen adult brain cadavers were used in this study. First, 2-mm-thick MRI sections were obtained, and the volume of the lentiform nuclei was measured on the obtained images. Then, agar-embedded brain specimens were cut into 4-mm-thick coronal sections using a microtome. The sections were scanned, and the volume of the lentiform nuclei was calculated using image processing software. The MRI-based and anatomical section-based metrics were compared.

Results: The mean right and left lentiform nucleus volumes on MRI were 5821.4 ± 590.5 mm^3 and 5781.8 ± 723.5 mm^3, respectively. The corresponding mean volumes calculated from the cadaveric sections were 5503.4 ± 595.5 mm^3 and 5332.3 ± 599.7 mm^3, respectively. There was no significant difference between the volume calculated from MRI and that obtained from the cadaveric section ($P < .001$). On MRI, the volumes of the right and left lentiform nuclei were not significantly different ($P = .681$). Similarly, the volumes of the right and left lentiform nuclei measured from cadaveric sections were not significantly different ($P = .069$).

Conclusion: This study showed a correlation between the measurement of the lentiform nucleus volume based on MRI and that calculated from anatomical sections. Our findings support the reliability of using MRI for stereotactic functional neurosurgical procedures.

Keywords: Anatomy, functional neurosurgery, lentiform nucleus, magnetic resonance imaging, stereology

INTRODUCTION

The lentiform nucleus (also referred to as the nucleus lentiformis) is a large, cone-shaped mass of gray matter that forms the central nucleus of the cerebral hemisphere, the convex base of which consists of the putamen and the apical part of the globus pallidus. The lentiform nucleus is divided into two parts. The inner part is called the globus pallidus, and the outer part is called the putamen. Globus pallidus appears lighter than the putamen because it contains a large amount of myelinated nerve fibers. The lentiform nucleus is bounded by the anterior limb of the internal capsule from the caudate nucleus and the posterior limb of the internal capsule from the thalamus.[1]The putamen is believed to play an additional role in memory formation, specifically muscle memory. For example, activities such as learning to ride a bicycle involve the use of putaminal nuclei. Globus pallidus, on the other hand, is involved in the execution of fine movements and preventing abnormal movements.[1]

The putamen and globus pallidus are more enriched in mitochondria, vascular nutrition, neurotransmitters, and chemical content compared to the other areas of the brain. Therefore, these have higher metabolic activity, leading to a higher rate of utilization of glucose and oxygen. Due to this feature, the lentiform nucleus is more vulnerable to systemic and metabolic disorders.[2]

Pathologies affecting the putamen and globus pallidum can lead to Parkinson's disease (PD) and other movement disorders. It is relatively easy to describe the clinical manifestations of the involvement of the internal capsule. However, it is relatively difficult to distinguish the patterns of clinical presentation resulting from the involvement of the putamen and globus pallidus.[3] Girround et al described two clinical syndromes occurring due to brain involvement limited to the lentiform nucleus: (i) behavioral disorder due to infarction of the globus pallidus and cognitive function disorders and (ii) motor (dystonia) and cognitive dysfunction due to the involvement of the putamen.[4] Bhatia and Marsden published a series of 240 patients with focal lesions in the basal ganglia. Dytonia and abulia (loss of the ability to make conscious decisions and move) were found to be the most common motor abnormalities with lentiform and caudate nuclei lesions in this investigation. Other behavioral problems are also common in lesions of the specified nucleus.[5]

Similarly, concomitant involvement of the putamen, caudate nucleus, thalamus, and parietal cortex may cause acute and subacute posthemiplegic focal dystonia or hemidystonia.[6] However, in most cases, the involvement of the internal capsule is due to the enlargement of the lesion, which affects the neighboring structures. Other motor disorders such as unilateral chorea,[7] hemichorea–hemibalismus, asterixis- acute motor stereotypes,[8] acute focal dystonias, and subacute parkinsonism,[9] have been reported after unilateral lesions of the lentiform nucleus. Globus pallidus lesions can cause behavioral and speech disorders. In most cases, motor disturbances may occur several months or years after the onset of the acute lesion.[4]

According to the published literature, putaminal lesions typically occur after head trauma. Ischemic stroke due to pure lesions of the putamen has rarely been reported.[4] Putaminal infarct usually progresses to adjacent tissues, creating a wider clinical picture.[4]

Apart from ischemic or hemorrhagic strokes and trauma, some neurodegenerative diseases can cause serious neurological pictures by affecting the basal nuclei. Among these, the best known are Wilson's disease,[10] Hallervorden–Spatz disease,[11] and Fahr's syndrome.[12]

Radiological methods are used for the diagnosis of both ischemic and hemorrhagic strokes as well as post-traumatic lesions in the brain, including basal nuclei. Although computed tomography is a practical and inexpensive method, it may not adequately demonstrate the changes in brain tissue, especially ischemic changes. Magnetic resonance imaging (MRI) is much more sensitive to brain parenchymal changes and is superior in terms of showing tissue-level changes.

Stereotactic surgery is an important minimally invasive neurosurgical method. It involves the localization of anatomical targets in the brain using an external, three-dimensional (3D) reference system. Stereotactic surgery allows access to deep-seated and small lesions without extensive craniotomy and damage to normal brain tissue. The value of stereotactic biopsy in neuro-oncology is undisputed, as it enables sampling of the required tissue without damaging the normal tissues, enabling accurate diagnosis and treatment. Although there are nuanced differences in the applied systems, the main underlying principle is always the same, i.e., accessing the target tissue by stereotactic methods based on geometric planning using radiological imaging (without direct visual access).

However, there are some pertinent unresolved issues related to the localization of the basal nuclei with stereotactic methods using cranial MRI. To what extent is it possible to accurately detect these target tissues anatomically? To understand this, it is instructive to compare the morphometric measurements of basal nuclei in cadaveric specimens with the morphometric measurements made in cranial MR images.

Functional neurosurgery and deep brain stimulation (DBS) are probably one of the fastest-growing areas of neurosurgery. Although these procedures (ablative or nonablative) are minimally invasive, they have many complications and side effects, such as infection, system malfunction, intracerebral hemorrhage, skull fracture, skin erosion, and foreign body reaction.[13-17] Among these complications, the inability to properly place the system (malposition) is related to the inability to accurately localize the target anatomical point. Therefore, in this study, we calculated and compared the volumes of lentiform nuclei stereologically by making radiological and then anatomical sections in cadaveric specimens and evaluated the results in terms of functional neurosurgical procedures.

Many published studies have measured brain basal nuclei volumes using MRI or CT. In most of these studies, volume changes in basal nuclei were performed for comparison in some disease states.[18-21] However, there are no in-depth studies involving the calculation of the lentiform nucleus volume in cadaver samples. In particular, we could not find any study that compared lentiform nucleus volumes by measuring them first in MRI and then in cadaver samples and emphasizing the importance of this in terms of functional neurosurgical procedures. In this respect, we believe that our study makes an important contribution to contemporary literature.

Purpose: To measure and compare the volume of the lentiform nucleus using MRI and the anatomical sections.

MAIN POINTS

- Functional neurosurgery is one of the fastest growing areas of neurosurgery. However, complications are encountered which are not negligible during the operations.
- Among these complications, the inability to place the system properly (malposition) is related to the inability to accurately localize the target anatomical point.
- Therefore, in this study, we calculated and compared the volumes of lentiform nuclei stereologically by first making radiological and then anatomical sections in cadaveric specimens.
- This study shows a correlation between measurement of lentiform nucleus volume based on MRI and those calculated from anatomical sections. Our findings support the reliability of functional neurosurgical procedures using MRI and stereotactic method.

METHODS

This study was approved by the Clinical Ethics Committee of Recep Tayyip Erdoğan University (approval no. 2022/173, dated October 6, 2022). The study was conducted using brain specimens removed by autopsy from 15 adult human cadavers. The age, sex, and disease status of the cadavers were unknown. These cadaver specimens were approximately 10 years old and were fixed in 10% formaldehyde. Two of the cadaver samples were excluded from the study because they were not of suitable quality. For the remaining 13 cadaver specimens, firstly, MRI images were obtained (section thickness: 2 mm; intervals of 1 mm) (Figure 1). These specimens were then embedded in agar. Then, 4 mm-thick sections were prepared with a microtome.

Magnetic Resonance Imaging Procedure

Imaging of the cadavers was performed using a 36-channel 1.5T MRI device (Discovery MR 750w, GEM-70, General Electric Company, USA). Turbo spin echo (T1 FLAIR) images with a section thickness of 2 mm were obtained in the coronal plane using a head coil (Figure 2). Imaging parameters were as follows: repetition time (TR): 2310; time to echo (TE): 8.1/Ef, EC: 1/135.7 kHz; inversion time (TI): 974; Head

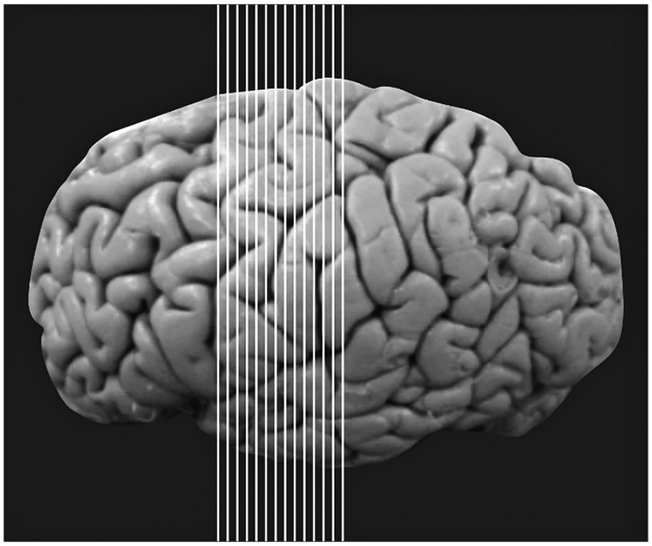

Figure 1. Obtaining TSE (T1 FLAIR) images with a section thickness of 2 mm by skipping 1 cm by segmentation method on coronal plane MRI. FLAIR, fluid-attenuated inversion recovery; MRI, magnetic resonance imaging; TSE, turbo spin echo.

24/FL: a; field-of-view (FOV): 24 × 21.6, 2.00 thk/1.00 sp, 60/06:25, and 320 × 224/2.00 number of excitations (NEX). The number of sections on which the lentiform nucleus appeared on MR images was calculated. Onis 2.5 [Onis Free Edition 2.5 Download—Onis.exe] and Image J (https://imagej.net/Downloads) software were then used to calculate the lentiform nucleus volume from the MR images. Onis 2.5 is an analytical program that rapidly converts images into DICOM format serially (Figure 3). Image J software is used for image analysis, processing, and surface area calculation in clinical and scientific studies (Figure 4).

Preparation of Cadaver Specimens

Agar (Trypticase Soy Agar, Merck) was prepared for the detection of the samples. For this process, 1.5% powdered agar was mixed in distilled water to prepare a solution. The solution was dissolved in a boiling water bath. Subsequently, it was sterilized in an autoclave at 121°C and then cooled to 50°C. The samples were placed in plastic boxes. The agar was poured so that it overflowed 2 cm at the edges of the samples. It was left to freeze for 6 hours at room temperature. A Bosch MAS9454M bslicing machine was used for cutting the cadaver specimens. Then, 4 mm-thick coronal sections were prepared (Figure 5). Sections thinner than 4 mm could not be obtained because they led to sample fragmentation. The obtained sections were scanned

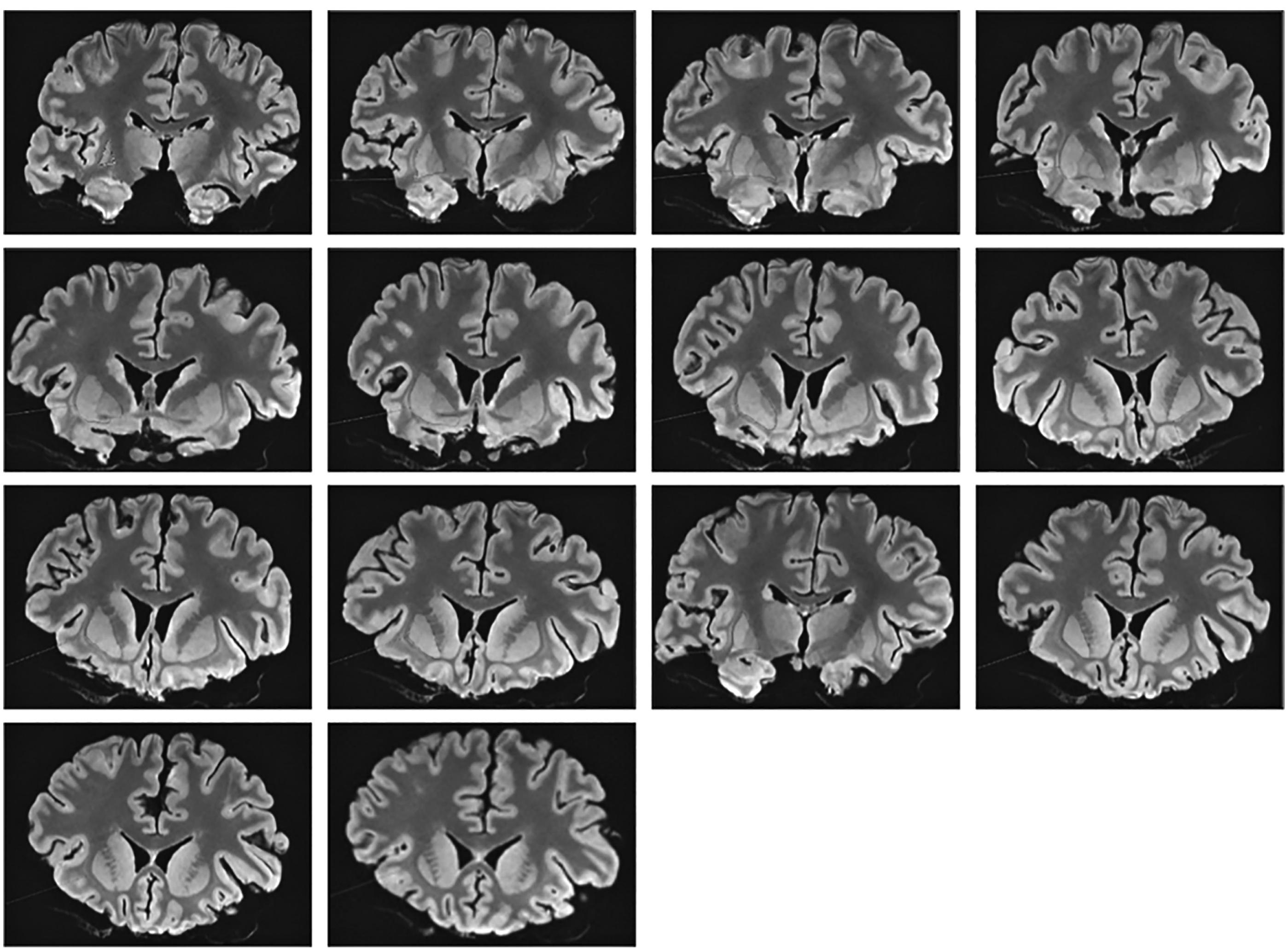

Figure 2. Sections in which lentiform nuclei are seen in the frontal plane in a sample cadaver on MRI. MRI, magnetic resonance imaging.

Figure 3. Evaluation of MR image in Onis 2.5 analysis program. MR, magnetic resonance.

using a scanner (Xerox, Workcentre 7428, USA), and the images were uploaded to a desktop computer (HP, ProDesk 600, G2, MT, USA) (Figure 6). The total number of sections obtained from each cadaver and the number of sections with lentiform nuclei were noted (Table 1). The Image J image program was used to set the scale and calculate the surface area on these images (Figure 7).

Calculation of Volume According to the Cavalieri Principle

The volumes of the lentiform nuclei were calculated using the Cavalieri principle and the planimetry technique on MRIs and cadaver cross-sectional images. For volume calculations, the surface areas of the lentiform nuclei on the MRIs converted to Cadaver and DICOM formats were calculated by the planimetry method using the Image J program (Figure 4). Each measurement was performed in a blinded fashion by the same researcher at least three times, and the average values were taken. The volumes of the lentiform nuclei were calculated by entering the sum of the surface areas in the following formula, based on the literature.[22,23]

$$V = t \times \sum A$$

where t represents the thickness of the successive sections and $\sum A$ represents the total surface area of the thalamus found in the section

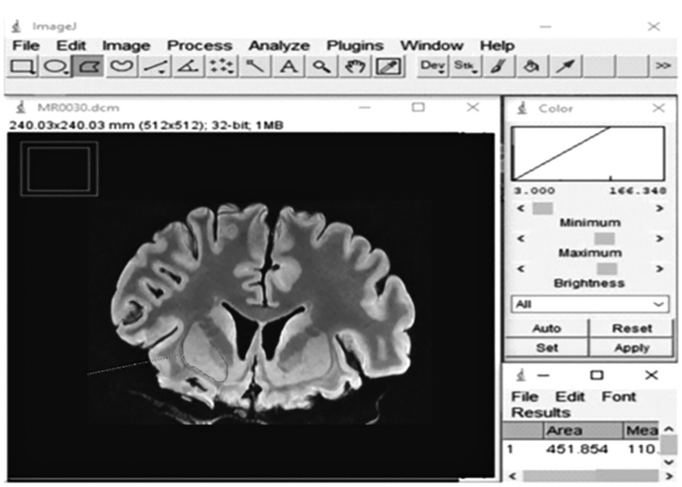

Figure 4. Evaluation of MR image in J image analysis program. MR, magnetic resonance.

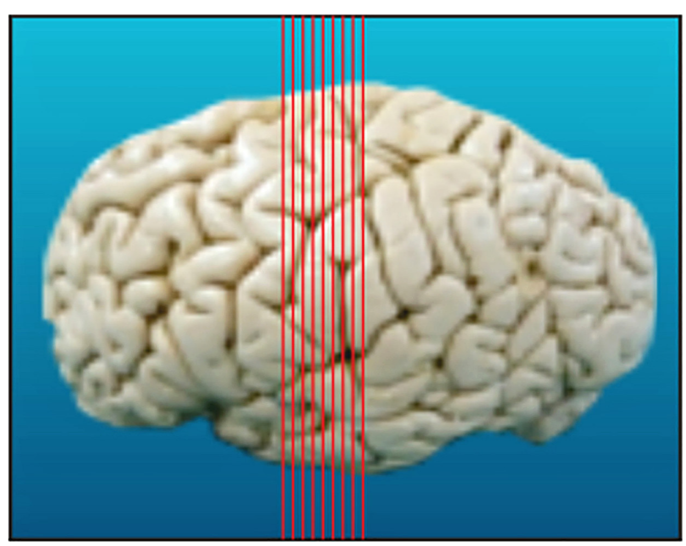

Figure 5. Sectioning 4 mm thick in a cadaver sample.

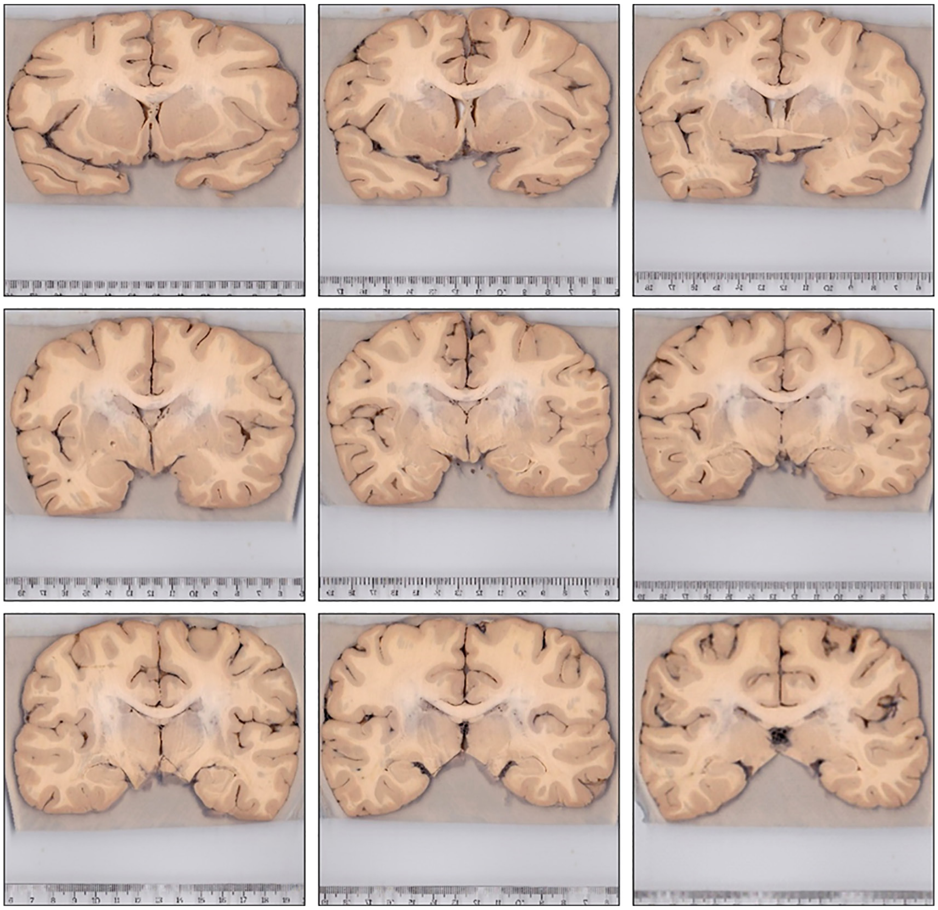

Figure 6. The appearance of lentiform nuclei for the fifth cadaver on coronal plane.

images. All data were entered into a pre-prepared Microsoft Excel spreadsheet containing the above formula, and the calculation was automatically performed. The volumes of the lentiform nuclei in each cerebral hemisphere were calculated separately.

Table 1. Sections Numbers of MRI and Cadaveric Specimens (n = 13)

Cadaver No.	The Total Section Number on MRI	The Total Section Number on Cadaver	The Number of Sections of the Right Lentiform Nucleus on MR	The Number of Sections of the Left Lentiform Nucleus on MR	The Number of Sections of the Right Lentiform Nucleus on Cadaver	The Number of Sections of the Left Lentiform Nucleus on Cadaver
1	58	42	14	13	9	9
2	56	38	12	13	8	8
3	55	38	14	13	8	9
4	51	36	11	11	7	7
5	52	37	12	13	9	9
6	54	36	12	12	7	8
7	52	35	11	11	7	7
8	50	36	12	13	6	7
9	59	39	15	15	8	9
10	60	36	14	14	9	10
11	45	37	12	13	8	8
12	60	37	14	15	8	7
13	58	41	13	12	9	9
Mean	54.61	37.53	12.69	12.92	7.84	8.23
Minimum–maximum	45-60	36-42	11-15	11-15	6-9	7-10
Total number	710	488	166	168	103	107

MRI, magnetic resonance imaging; n, number of cadavers.

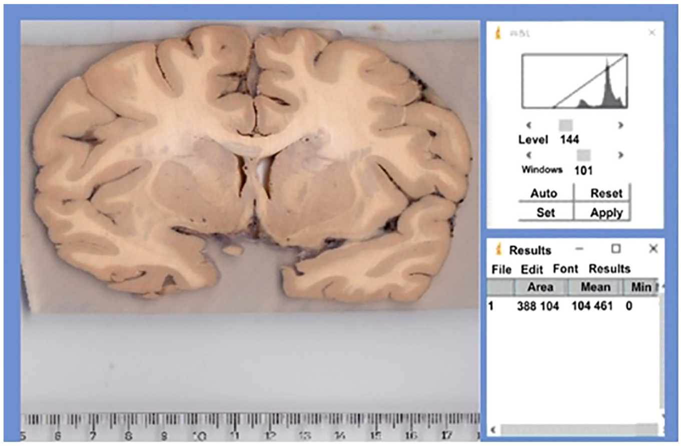

Figure 7. Calculation of the surface area of lentiform nuclei in cadaveric sections with image J program.

Statistical Analysis

Results are presented as mean ± standard deviation, or median (max-min) for continuous variables. Comparisons between right- and left-sided measurements were made using the paired *t*-test. First, the relationship between MRI, and cadaver measurements was examined using the Pearson correlation coefficient, and the results were presented as r(*P*). Then, reliability analysis was performed using a two-way mixed effects model in which human effects were considered random and measurement effects were fixed. The model was used to calculate the Absolute Agreement Intra-Class Correlation Coefficient (ICC). *P* values < .05 were considered statistically significant. Statistical analyses were performed using IBM SPSS v 19 software (IBM Software, NY, USA).

RESULTS

The total number of MRI and anatomical sections of each cadaver and the number of sections in which the lentiform nuclei were seen are shown in Table 1. In MRI, the total number of cadaver sections was 710; the mean number of sections was 54.61 (range: 45-60); the total number of sections with the right lentiform nuclei was 166; the average was 12.69 (range: 11-15); and the total number of sections with the left lentiform nuclei was 168; the mean was 12.92 (range: 11-15). The total number of sections obtained from cadaver specimens was 488, mean 37.53 (range: 36-42); the total number of sections with the right lentiform nuclei was 103, mean 7.84 (range: 6-9). The total number of sections with the left lentiform nuclei was 107, mean 8.23 (range: 7-10). The mean volumes of the right and left lentiform nuclei on MRI were 5821.4 ± 590.5 mm^3 (range: 4820-6755) and 5781.8 ± 723.5 mm^3 (range: 4232-7064), respectively. In cadaveric specimens, the right, and the left lentiform nucleus volumes were 5503.4 ± 595.5 mm^3 (range: 4336-6532) and 5332.3 ± 599.7 mm^3 (range: 3940-6444), respectively (Table 2). For the right lentiform nucleus, there was a statistically significant agreement between the two measurement techniques ($P < .001$; ICC $\rho = 0.619$). Similarly, for the left lentiform nucleus, the agreement between the two measurement techniques was statistically significant ($P < .001$; ICC $\rho = 0.714$) (Table 3).

Table 3. Volume of the Lentiform Nuclei with Different Measurement Techniques (MRI and Cadaveric Section)

Measurement Technique	Cadaveric Section	MRI	r(p)**
Right lentiform nucleus	5503.4 ± 595.5 5504.0 (4336.0-6532.0)	5821.4 ± 590.5 6019.0 (4820.0-6755.0)	.95 (<.001
Left lentiform nucleus	5332.3 ± 599.7 5212.0 (3940.0-6444.0)	5781.8 ± 723.5 5745.0 (4232.0-7064.0)	.89 (<.001)
*P**	.069	.681	

MRI, magnetic resonance imaging.

*Paired samples test for right and left. **Correlation between cadaver and MRI sections.

DISCUSSION

In this study, we measured the lentiform nucleus volumes in coronal sections of 13 human cadaver brains using a 1.5T MRI device. Then, the lentiform nucleus volumes were measured in the anatomical coronal sections of the same cadaver samples using a microtome. The results obtained with the 2 methods were compared, and the importance of these results in terms of functional neurosurgical procedures was investigated.

Table 2. MRI and Cadaver Lentiform Nucleus Volumes (mm^3) (n = 13)

	MRI		Cadaver Sections	
Cadaver No.	Right	Left	Right	Left
1	5605.0	5413.0	5396.0	5040.0
2	5279.0	5362.0	4824.0	5212.0
3	6755.0	6692.0	6532.0	6444.0
4	6053.0	5745.0	5924.0	5532.0
5	4872.0	5132.0	4828.0	4976.0
6	6019.0	5553.0	5420.0	5164.0
7	5969.0	5581.0	5844.0	5100.0
8	6034.0	6062.0	5632.0	5684.0
9	6288.0	6408.0	5908.0	6004.0
10	4820.0	4232.0	4336.0	3940.0
11	6516.0	7064.0	6116.0	5644.0
12	6044.0	6108.0	5504.0	5532.0
13	5424.0	5812.0	5280.0	5048.0
Mean ± SD	5821.4 ± 590.5	5781.8 ± 723.5	5503.4 ± 595.5	5332.3 ± 599.7
Medyan	6019.0	5745.0	5504.0	5212.0
Minimum–maximum	4820.0-6755.0	4232.0-7064.0	4336.0-6536.0	3940.0-6444.0

MRI, magnetic resonance imaging; n, number of cadavers.

Understanding the brain structures in 3D and performing volumetric measurements is of great importance for the correct diagnosis and treatment of brain diseases. Two-dimensional tools (for example, anatomy books) or traditional 3D tools (e.g., plastic models) are not sufficient to understand the 3D structures of the brain. For this purpose, the availability of high-resolution MRI methods is important. MRI-based volume measurement is now increasingly used to investigate neuroanatomical structures in patients with neurological and psychiatric disorders such as PD, schizophrenia, Alzheimer's disease (AD), and epilepsy.[23-25]

Automated segmentation methods using MRI have been described in many studies. Calmon and Roberts reported a segmentation method for lateral ventricles on coronal plane MRI.[26] Stokking et al developed morphology-based brain segmentation using T1-weighted MRI for fully automated segmentation.[27] Webb et al reported an automatic partitioning method for the detection of hippocampal atrophy.[28] Each of these methods is based on the fragmentation of the target object in each MRI, obtained in different indexes.

Wang et al published a study of 1000 patients (age range, 18-70 years) to investigate various diseases related to the lentiform nucleus in the Chinese population. The patients were divided into 5 age groups (18-30, 31-40, 41-50, 51-60, and 61-80). Each group consisted of 100 men and 100 women. All volunteers underwent MRI examination using a T1-weighted 3D magnetization-prepared rapid acquisition gradient echo array. The relationship of the lentiform nucleus volume with age and sex was analyzed. The mean left and right putamen volumes were 4811.59 ± 588.99 mm^3 and 4763.11 ± 587.59 mm^3, respectively, and the volume of the left putamen was greater than that of the right putamen. The mean left and right globus pallidus volumes were 1591.31 ± 226.81 mm^3 and 1627.28 ± 235.06 mm^3, respectively, and the right globus pallidus volume was larger. The mean volumes of the left and right putamen and left and right globus pallidus in men were 4962.72 ± 598.49 mm^3, 4909.83 ± 600.54 mm^3, 1623.24 ± 234.16 mm^3, and 1663.18 ± 243.56 mm^3, respectively. In women, these measurements were 4663.65 ± 540.49 mm^3, 4619.28 ± 537.59 mm^3, 1560.00 ± 215.04 mm^3, and 1592.09 ± 221.06 mm^3, respectively. The putamen and globus pallidus volumes were larger in men. The volumes of the left and right putamen, as well as the left and right globus pallidus, showed a decrease with age. The lentiform nucleus volume was found to be larger in men than in women. In addition, the lentiform nucleus volumes were found to decrease with aging.[18]

Ertekin et al measured and compared the lentiform nucleus volumes in healthy people and people with PD using both volumetric and semiautomatic segmentation methods. In the control group (healthy people), the mean lentiform nucleus volume calculated by the point counting method using a control object in MRI was 7.52 ± 1.14 cm^3. In the PD group, the corresponding mean value was significantly smaller (6.40 ± 1.55 cm^3, $P < .05$). Based on the semiautomatic segmentation results, the mean lentiform nucleus volume in patients with PD (6.52 ± 1.38 cm^3) was also significantly smaller than that in healthy humans (7.43 ± 0.87 cm^3; $P < .05$).[19]

Derrek et al conducted a study enrolling 706 patients with AD and 639 young healthy volunteers to investigate the relationship between the lentiform nucleus volume and genome-wide. They measured the volume by taking 58 images with the segmentation method in a 1.5T MRI. In patients with AD, the lentiform nucleus volume was 6422.2 ± 723.9 mm^3 on the left and 6450.9 ± 686.9 mm^3 on the right, and they found a strong correlation between the two. In healthy young people, the corresponding volume measurements were 6554.4 ± 744.8 mm^3 on the left and 6729.5 ± 765.4 mm^3 on the right, with a strong correlation between the left and right lentiform nucleus volumes. Although the lentiform nuclei of patients with AD were smaller than those of healthy individuals, the difference was not statistically significant.[20]

In his doctoral thesis, Ekiz compared the volume ratio of the basal nuclei to the whole brain on the left and right sides in individuals aged 20-40 years. The mean volumes of the right and left globus pallidus in women were 1471 ± 161.7 mm^3 and 1447.4 ± 157.7 mm^3, respectively. The corresponding values in men were 1611.1 ± 119.0 mm^3 and 1571.7 ± 120.4 mm^3, respectively. The right and left putamen volumes in women were 4056.0 ± 328.5 mm^3 and 4343 ± 417.1 mm^3, respectively. The corresponding values in men were 4504 ± 278.9 mm^3 and 4817.5 ± 380.0 mm^3, respectively.[21]

The main aim of the present study was to compare the total volume measurement values in MRI sections with those obtained with anatomical sections of cadaver samples prepared using a microtome. The mean lentiform nucleus volume measurements on MRI were 5821.4 ± 590.5 mm^3 on the right and 5781.8 ± 723.5 mm^3 on the left. The corresponding measurements in cadaveric specimens were 5503.4 ± 595.5 mm^3 and 5332.3 ± 599.7 mm^3, respectively (Table 2). On comparing the measurements in MRI and cadaver samples, there was no significant difference between the right and left lentiform nucleus volumes, and there was a significant correlation between the two sides in this respect (Table 3).

Comparing the MRI-based volume measurements, these values are smaller than the values reported by Wang, Ertekin, Derrek, and Ekiz. This is likely attributable to the shrinking of the cadaver samples due to their storage in formaldehyde for 10 years, as seen in previous studies.[29]

Since information regarding the cadaver samples' age, race, and disease status was not available, it was impossible to make comparisons as in the previous studies. In any case, the purpose of our study was not to make comparisons between age, sex, and diseased and healthy groups.

On reviewing the literature, we found a comprehensive study that measured and compared the volumes of the thalamus by first using the segmentation technique in MRI and then making sections on cadavers using the planimetry technique.[30] However, we did not find a similar in-depth study involving the lentiform nucleus volume measurements in cadaver samples. Only Sürücü et al measured the dimensions of the lentiform nucleus in the horizontal and coronal planes in 3D CT in a human cadaveric brain but did not calculate the volume values.[31] Chung et al measured the dimensions of the lentiform nucleus in the horizontal and coronal planes at 0.04 mm intervals in a female cadaveric brain with 3T MRI and diffusion tensor MRI methods, but they did not measure volume either.[32]

In this study, the number of 2-mm sections obtained on MRI was higher than the number of anatomical sections obtained using a microtome. This was due to section fragmentation while attempting to prepare 2-mm-thick sections in cadaver samples with a microtome. Therefore, we prepared 4-mm-thick sections. The total number of sections on MRI was 710; the total number of sections showing the lentiform nucleus was 166 on the right side and 168 on the left side (Table 1). The total number of sections obtained by cutting cadaver specimens with a microtome was 488; the total number of sections showing the lentiform nucleus was 103 on the right and 107 on the left (Table 1). There was no significant difference between the right and left sides with respect to the number of sections obtained with the MRI and microtome. The anatomical and functional asymmetry between the right and left hemispheres of the human brain is well documented. This asymmetry has been reported between the volumes of the right and left basal nuclei.[33] In addition, there may be measurement differences due to differences in the position of cadavers during MRI and superimposition during imaging.[26]

Various stereological methods have been developed for the volumetric analysis of structures in the cadaveric brain. The Cavalieri method is one of the most reliable and frequently used methods. It is a highly sensitive and unbiased method for quantitative measurements.[34,35] In this method, parallel and equal-thickness portions of a body are taken, and the volume is calculated based on the total number of cross-sectional areas and the section thickness. Computed tomography, MRI, or ultrasonography cross-sectional imaging can be used to calculate the volume of an object using the Cavalieri principle.[23] Due to these properties, the Cavalieri method was used for volumetric measurements of cadaver samples in this study. In this study, 13 adult cadaver brain samples were examined. The samples were segmented on 1.5T MR devices, and after measuring the lentiform nucleus volumes, cadaver sections were prepared, and the lentiform nucleus volumes were compared stereologically.

Importance of This Study

Functional neurosurgical procedures, including ablative procedures and nonablative procedures (such as DBS), have many complications and side effects. These can be classified into 5 main groups: (i) Relatively rare natural side effects that may develop after the application of the system. These include unresponsiveness to DBS, stimulation-induced dyskinesia and dystonia, speech disorder, axial symptoms (gait disturbance, festination, freezing), ocular disorders (ocular deviation and eye opening apraxia), and psychiatric disorders (depression, anxiety, apathy, aggressive behavior, manic episodes, and impulse control disorder). (ii) Natural complications of the surgical procedure. These include infection, system malfunction, intracerebral hemorrhage, skull fracture, skin erosion, and foreign body reactions.[13-17] (iii) Complications due to the surgical technique applied and the inadequacy of the system (electrode breakage, etc.). These are related to the experience or working methods of the surgical center.[14] (iv) Factors related to the operator's skill and experience: e.g., system malposition resulting in the inability to accurately localize the target anatomical point. (v) Wrong patient selection. These interventional methods are applied to patients who are resistant to medical treatment in the mid-advanced stage of the disease. Additional clinical improvement may not be observed if these interventional methods are applied in the early stages and in patients who respond positively to medical treatment. Among these complications, the inability to place the system properly prevents the accurate localization of the target point. From this perspective, our results are important.

Study Limitations

Some limitations of this study should be considered while interpreting the results: (i) The age and sex of the cadaver specimens were unknown. However, this was not a significant handicap, considering the purpose of this study. (ii) The history of any ischemic, traumatic, or neurodegenerative disease in the cadaver samples was not available. (iii) The samples used were not fresh cadaver samples. After the postmortem examination, the cadavers were stored in formaldehyde for 10 years. This may have led to a progressive shrinking of samples over time, resulting in relatively smaller measurement values. However, the volume measurements obtained in previous studies using MRI were not significantly different from those in this study. (iv) Attempts to prepare 3-mm-thick sections with a microtome led to section fragmentation. Therefore, 4 mm-thick anatomical sections were prepared, while the MRI sections were 4 mm thick. Although this did not affect the total volume values of the lentiform nuclei, it can be seen as a limitation of this study. (v) The MRI device used in this study was 1.5 Tesla. The use of an MRI device with a higher resolution would have provided better images. For example, it would be possible to better distinguish between the putamen and the globus pallidus on a higher-resolution MRI device. However, only the 1.5T MRI device was available at our institution.

According to the results we obtained from this study, a significant correlation was found between the lentiform nucleus volumes measured using the MRI method and the volume measurements obtained by making anatomical sections. Our findings support the reliability of the DBS procedure performed using MRI with stereotactic guidance.

Ethics Committee Approval: Ethics committee approval was received for this study from the ethics committee of Recep Tayyip Erdoğan University (Date: October 6, 2022, Number: 2022/173).

Informed Consent: The cadaver specimens and MRI images used in the study were obtained from the relevant university's cadaver unit. The cadavers' names and surnames are not featured in any of the photographs. As a result, the permission form was omitted.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – S.K.; Design – S.K.; Supervision – S.K., O.B.; Resources – S.K.; Materials – S.K.; Data collection and/or Processing – S.K., F.B.Ç.; Analysis and/or Interpretation – S.K., O.B., S.D.; Literature Search – S.K., O.B.; Writing Manuscript – O.B., S.D.; Critical Review – O.B., M.F.Ö.; Other – M.F.Ö.

Declaration of Interests: The authors declare that they have no competing interest.

Funding: The authors declared that this study has received no financial support.

REFERENCES

1. Snell RS. *Clinical Neuroanatomy*. Wolters Kluwer Health/Lippincott Williams & Wilkins; 2022.
2. Hegde AN, Mohan S, Lath N, Lim CCT. Differential diagnosis for bilateral abnormalities of the basal ganglia and Thalamus. *RadioGraphics*. 2011;31(1):5-30. [CrossRef]
3. Moulin T, Bogousslavsky J, Chopard JL, et al. Vascular ataxic hemiparesis: a reevaluation. *J Neurol Neurosurg Psychiatry*. 1995;58(4):422-427. [CrossRef]
4. Giroud M, Lemesle M, Madinier G, Billiar T, Dumas R. Unilateral lenticular infarcts: radiological and clinical syndromes, aetiology, and prognosis. *J Neurol Neurosurg Psychiatry*. 1997;63(5):611-615. [CrossRef]
5. Bhatia KP, Marsden CD. The behavioral and motor consequences of focal lesions of the basal ganglia in man. *Brain*. 1994;117(4):859-876. [CrossRef]
6. Marsden CD, Obeso JA, Zarranz JJ, Lang AE. The anatomical basis of symptomatic hemidystonia. *Brain*. 1985;108(2):463-483. [CrossRef]
7. Chang MH, Chiang HT, Lai PH, Sy CG, Lee SS, Lo YY. Putaminal petechial haemorrhage as the cause of chorea: a neuroimaging study. *J Neurol Neurosurg Psychiatry*. 1997;63(3):300-303. [CrossRef]
8. Maraganore DM, Lees AJ, Marsden CD. Complex stereotypies after right putaminal infarction: a case report. *Mov Disord*. 1991;6(4):358-361. [CrossRef]

9. Kulisevsky J, Berthier ML, Avila A, Roig C. Unilateral parkinsonism and stereotyped movements following a right lenticular infarction. *Mov Disord*. 1996;11(6):752-754. [CrossRef]
10. Brewer GJ. *Wilson's Disease: A Clinician's Guide to Recognition, Diagnosis, and Management*. Kluwer Academic, Boston; 2001.
11. Hogarth P, Kurian MA, Gregory A, et al. Consensus clinical management guideline for pantothenate kinase-associated neurodegeneration (PKAN). *Mol Genet Metab*. 2017;120(3):278-287. [CrossRef]
12. Warren JD, Mummery CJ, Al-Din AS, Brown P, Wood NW. Corticobasal degeneration syndrome with basal ganglia calcification: Fahr's disease as a corticibasal look-alike? *Mov Disord*. 2002;17(3):563-567. [CrossRef]
13. Constantoyannis C, Berk C, Honey CR, Mendez I, Brownstone RM. Reducing hardware-related complications of deep brain stimulation. *Can J Neurol Sci*. 2005;32(2):194-200. [CrossRef]
14. Hariz MI. Complications of deep brain stimulation surgery. *Mov Disord*. 2002;17(3)(suppl 3):S162-S166. [CrossRef]
15. Morishita T, Foote KD, Burdick AP, et al. Identification and management of deep brain stimulation intra- and postoperative urgencies and emergencies. *Parkinsonism Relat Disord*. 2010;16(3):153-162. [CrossRef]
16. Fenoy AJ, Simpson RK Jr. Risks of common complications in deep brain stimulation surgery: management and avoidance. *J Neurosurg*. 2014;120(1):132-139. [CrossRef]
17. Chan DT, Zhu XL, Yeung JH, et al. Complications of deep brain stimulation: a collective review. *Asian J Surg*. 2009;32(4):258-263. [CrossRef]
18. Wang GK, Chen N, Wang X, Zhuo Y. Measuring the volume of the lentiform nucleus in healthy Chinese adults based on high-resolution MRI. *Chin J Med Imaging Technol*. 2012;28(1):15-18.
19. Ertekin T, Acer N, İçer S, Vurdem ÜE, Çınar Ş, Özçelik Ö. Volume Estimation of the Subcortical Structures in Parkinson's Disease Using Magnetic Resonance Imaging: Methodological Study. *Neurol Asia*. 2015;20(2):143-153.
20. Hibar DP, Stein JL, Ryles AB, et al. Genome-wide association identifies genetic variants associated with lentiform nucleus volume in N=1345 young and elderly subjects. *Brain Imaging Behav*. 2013;7(2):102-115. [CrossRef]
21. Ekiz Y. *20-40 Yaş Arası Bireylerde Bazal Çekirdeklerin Hacminin Tüm Beyne Olan Hacim Oranı ve Sağ Sol Kıyaslanması Doktora tezi*. İstanbul Medipol Üniversitesi, İstanbul. 2020.
22. Şahin B, Emirzeoglu M, Uzun A, et al. Unbiased estimation of the liver volume by the Cavalieri principle using magnetic resonance images. *Eur J Radiol*. 2003;47(2):164-170. [CrossRef]
23. Acer N, Sahin B, Baş O, Ertekin T, Usanmaz M. Comparison of three methods for the estimation of total intracranial volume: stereologic, planimetric, and anthropometric approaches. *Ann Plast Surg*. 2007;58(1):48-53. [CrossRef]
24. Bas O, Acer N, Mas N, Karabekir HS, Kusbeci OY, Sahin B. Stereological evaluation of the volume and volume fraction of intracranial structures in magnetic resonance images of patients with Alzheimer's disease. *Ann Anat*. 2008;191:186-195.
25. Bernasconi N, Andermann F, Arnold DL, Bernasconi A. Entorhinal cortex MRI assessment in temporal, extratemporal, and idiopathic generalized epilepsy. *Epilepsia*. 2003;44(8) :1070-1074. [CrossRef]
26. Calmon G, Roberts N. Automatic measurement of changes in brain volume on consecutive 3D MR images by segmentation propagation. *Magn Reson Imaging*. 2000;18(4):439-453. [CrossRef]
27. Stokking R, Vincken KL, Viergever MA. Automatic morphology-based brain segmentation (MBRASE) from MRI-T1 data. *Neuroimage*. 2000;12(6):726-738. [CrossRef]
28. Webb J, Guimond A, Eldridge P, et al. Automatic detection of hippocampal atrophy on magnetic resonance images. *Magn Reson Imaging*. 1999;17(8):1149-1161. [CrossRef]
29. Jonmarker S, Valdman A, Lindberg A, Hellström M, Egevad L. Tissue shrinkage after fixation with formalin injection of prostatectomy specimens. *Virchows Arch*. 2006;449(3):297-301. [CrossRef]
30. Kayacı S, Bas O, Celiker FB,et al. Comparison of Thalamus volume on magnetic resonance and cadaveric section images. *Turk Neurosurg*. 2020;30(4):491-500. [CrossRef]
31. Sürücü HS, Aldur MM, Çelik HH. Three-dimensional reconstruction of the lentiform nucleus from serial sections in man. *Folia Morphol*. 2002;61(3):153-156.
32. Chung BS, Han M, Har D, Park JS. Advanced Sectioned Images of a Cadaver Head with voxel Size of 0.04 mm. *J Korean Med Sci*. 2019;34(34):e218. [CrossRef]
33. Vernaleken I, Weibrich C, Siessmeier T, et al. Asymmetry in dopamine D(2/3) receptors of caudate nucleus is lost with age. *Neuroimage*. 2007;34(3):870-878. [CrossRef]
34. Gundersen HJ, Jensen EB. The efficiency of systematic sampling in stereology and its prediction. *J Microsc*. 1987;147(3):229-263. [CrossRef]
35. Mayhew TM, Gundersen HJG. 'If you assume, you can make an ass out of u and me': a decade of the disector for stereological counting of particles in 3D space. *J Anat*. 1996;188(1):1-15.