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Ultrasound and Magnetic Resonance Imaging of the Tongue in Obstructive Sleep Apnoea

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Abstract: To examine the geometrical parameters of the tongue in obstructive sleep apnoea (OSA) based on sex, age and BMI parameters and ultrasound (US) and MRI. The presence of OSA and tongue-based obstruction can be predicted using these parameters. Of 100 patients, 64% were diagnosed with OSA according to overnight polysomnography. MRI and US devices were used to measure tongue parameters. The location of the obstruction was identified using drug-induced sleep endoscopy. Statistical analysis was performed using the quadratic discriminant analysis. Men presented higher tongue volumes and axial diameter during Müller's maneuver (MM) of US and coronal diameter of the MRI. In women, all examined MRI parameters were significantly correlated with apnoea-hypopnea index (AHI). A stronger correlation between BMI and AHI parameters was observed in women than in men. Using our algorithm, which includes tongue parameters and anthropometric values, the presence of OSA could be predicted in 91% with US and 82% with MRI. The detection of tongue-based obstruction was successful in 89% using US and 87% using MRI, whereas tongue-based obstruction was successful in 70% using US. Using MRI and US of the tongue combined with basic anthropometric parameters, the presence of OSA and tongue-based obstruction can be identified with high precision.

Keywords: artificial intelligence; drug-induced sleep endoscopy; MRI; obstructive sleep apnoea; tongue; ultrasound; machine learning

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1. Introduction

Obstructive sleep apnoea is a heterogenic disorder; its origin is a partial (hypopnea) or a total (apnoea) collapse of the upper airways, resulting in hypoxia, hypercapnia, and sleep fragmentation [1]. The complex pathophysiological background behind OSA is responsible for its individual phenotype, including anatomical and non-anatomical factors (e.g., narrow diameters of the upper airways, low arousal threshold, high loop gain, and the reduced upper airway muscle dilation during sleep). The collapsibility of the upper airways can be determined by the passive critical closing pressure (Pcrit), which means the pressure at which the upper airways collapse and the airflow is reduced, and can be measured by the continued positive airway pressure [2].

The tongue is a typical location of an obstruction of the upper airways and is therefore responsible for the obstructions in 58% [3]. The tongue can cause obstruction due to its increased volume, blocking the upper airways in a fall-back position, compromising the tongue and its location in the surrounding anatomical structures [4]. The genioglossus muscle is the largest extrinsic tongue muscle and, therefore, the largest upper airway dilatator muscle, which, in the case of damaged functioning, results in an obstruction of the upper airways and OSA. [5]. Obesity is one of the essential risk factors for OSA, resulting in fat deposits in the soft tissues surrounding the upper airways, consequently in the tongue, resulting in its increasing volume. For example, increased tongue volume can be a risk factor for difficult intubation, which can be identified using medical imaging methods. The role of other risk factors for OSA, e.g., age or sex, has been particularly investigated. Examining the tongue in awake participants using CT or MRI allows analysis of its static parameters. However, using an ultrafast CT or cine MRI gives the possibility of dynamic measurements that are useful in terms of anatomical factors in the OSA background [6].

The present study aimed to examine the geometric parameters, such as diameters and volumes of the tongue, tongue fat% and fat in the midsagittal area of the tongue, depending on gender, age and BMI in OSA. A further objective was to analyse the role of the tongue in upper airway obstruction and OSA using US and MRI on awake participants. Using the US and MRI parameters of the tongue results in a complex pattern, although modern statistical methods can correctly interpret these data. The results of this investigation are especially significant in OSA cases where OSA was not previously detected, although MRI and US measurements were applied with another indication than OSA examination.

2. Materials and Methods

2.1. Participants

In this prospective investigation, 100 adult patients (74 men and 26 women, aged 42.15 ± 11.7 years) visited the Department of Otolaryngology and Head and Neck Surgery of Semmelweis University due to snoring and/or possible OSA were enrolled. Exclusion criteria included previous oral or otorhinolaryngological surgeries, muscle or connective tissue diseases, hypothyroidism, neurological or psychiatric disorders, pregnancy, craniofacial malformations, facial trauma, claustrophobia, and having any metal implants in the body. All participants have obtained written informed consent and the study was approved by the Hungarian Research Ethics Authority (National Institute of Pharmacy and Nutrition (2788/2019)).

2.2. Sleep Test

Overnight polysomnography was performed in the Department of Pulmonology using a SOMNOscreen Plus PSG device (SOMNOmedics GMBH, Randersacker, Germany) controlled by medical staff. The examination results were interpreted according to the recommendation of the American Academy of Sleep Medicine (AASM) by the same experienced sleep specialist, who was blinded to all previous examination results of the patients. The severity of OSA can be defined using the apnoea-hypopnea index (AHI), calculated based on the apnoea and hypopnoea periods per hour. Apnoea means at least a reduction in nasal airflow of 90% for 10 s or more, whereas hypopnoea is defined as a 30% reduction accompanied by microarousals or at least 3% desaturation [7]. Due to the relatively low number of subjects in this study, our patients were divided into OSA (AHI $\geq$ 5) and non-OSA groups (AHI < 5).

2.3. Ultrasound

The US examinations were performed using a Samsung RS85 ultrasound device (Samsung Medison, Seoul, Korea), with a CA1-7A convex transducer (1–7 MHz), in grayscale B mode. The examinations were performed by radiologists, who were experienced in head and neck US diagnostics, and were blinded to previous examinations. The patients were examined in a supine position, with the transducer placed in the submental region, between the hyoid bone and the mandibular symphysis. The patients were instructed to breathe normally and avoid tongue movements, speaking, and swallowing. After measuring the coronal, sagittal, and axial diameters of the tongue at rest, the patients were instructed to perform the Müller's manoeuvre, which means forced inspiration with a closed glottis after forced expiration, which simulates upper airway obstruction. Thus, we it was possible to measure the diameters during MM, and this examination was performed twice. The US device automatically calculated the diameters and volumes of the tongue during both measurements (see Figure 1).

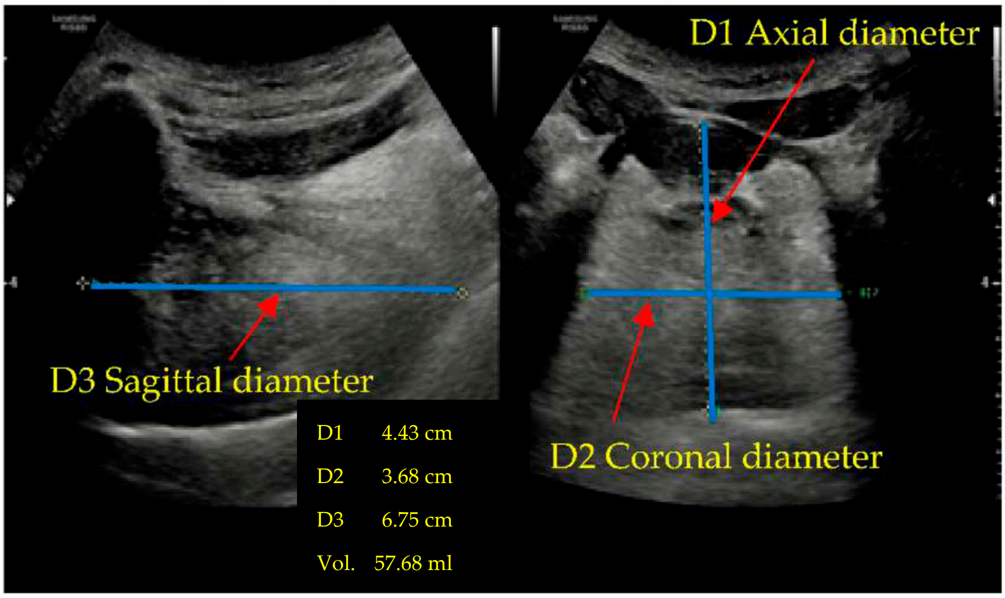


Figure 1. US image of the tongue in grayscale mode B. The axial, sagittal diameters and volume are visualised (i.e., D1 axial, D2 coronal and D3 sagittal diameters; taken from our data).

2.4. MRI

MRI measurements were carried out at the Medical Imaging Centre of Semmelweis University using a Philips Ingenia 1.5 T MRI device. MRI scans were conducted from the posterior nasal spine to the hyoid bone. As part of the neck MRI study, measurements of sagittal T2 TSE, STIR and T1 TSE, coronal T1 TSE (each with a slice thickness of 3.5 mm without gaps), and axial T2 SPIR, T1 TSE, and DWI (with a slice thickness of 3 mm with a gap of 1.5 mm) were performed. A Philips IntelliSpace Portal (Philips Healthcare, Best, The Netherlands) was used to analyse the scans and an experienced radiologist interpreted the results. The patients were examined in supine position and instructed to breathe normally through their noses.

The sagittal diameter of the tongue was measured in the anteroposterior directions, as the longest diameter between the apex and the base of the tongue. Tongue thicknesses were defined as the longest diameters between the origin of the genioglossus muscle and the surface of the tongue. Both calculations were based on T2 and T1 TSE weighted images.

The coronal and axial diameters were defined as the longest laterolateral diameters in the coronal or axial direction in coronal T1 TSE, axial T2 SPIR and T1 TSE scans. The midsagittal area (cm^2) means the surface measured in the middle line of the sagittal axis, which was determined using the DICOM viewer software. The volume of the tongue was calculated using a semiautomatised analysis software (Philips IntelliSpace Portal Multi-Modality Viewer). The measurement was based on the calculation of the Region of Interest and volume rendering.

Tongue Fat% was defined as the ratio of the area on the midsagittal axis that shows the density of fat and the total surface of the tongue. In T1 weighted images, continuous adipose tissue in the tongue can be relatively well differentiated, and tongue Fat% was calculated using the fat area in the middle of the tongue using sagittal images and scaled to the midsagittal tongue area (Figure 2).

2.5. Drug-Induced Sleep Endoscopy

Drug-induced sleep endoscopy was performed in an operating room by an experienced otorhinolaryngologist under general anaesthesia. The patients were lying in a supine position and 1.5 mg/kg propofol was used intravenously. The endoscopy was started after the first appearance of a snoring sound, using an Olympus 3.5 mm flexible endoscope inserted through the nose and leading to the larynx. The interpretation of the results was based on VOTE classification [8].

2.6. Statistical Analysis

A combination of standard methods for healthcare statistics was applied for data processing [9]. A descriptive statistic was carried out as the first analysis step. Levene's test defined the groups' homogeneity of variance. In the case of homogeneity, the Bonferroni test was used, and in the case of inhomogeneity, Tamharane's T^2 test was used. The stochastic relationships between the different variables were determined by Pearson's correlation. Patients' classification was performed using quadratic discriminant analysis. All analyses were performed using the R software system. Even though the relatively limited number of the data, we were able to analyse the statistical correlation at three different levels (i.e., 90, 95 and 99% probability).

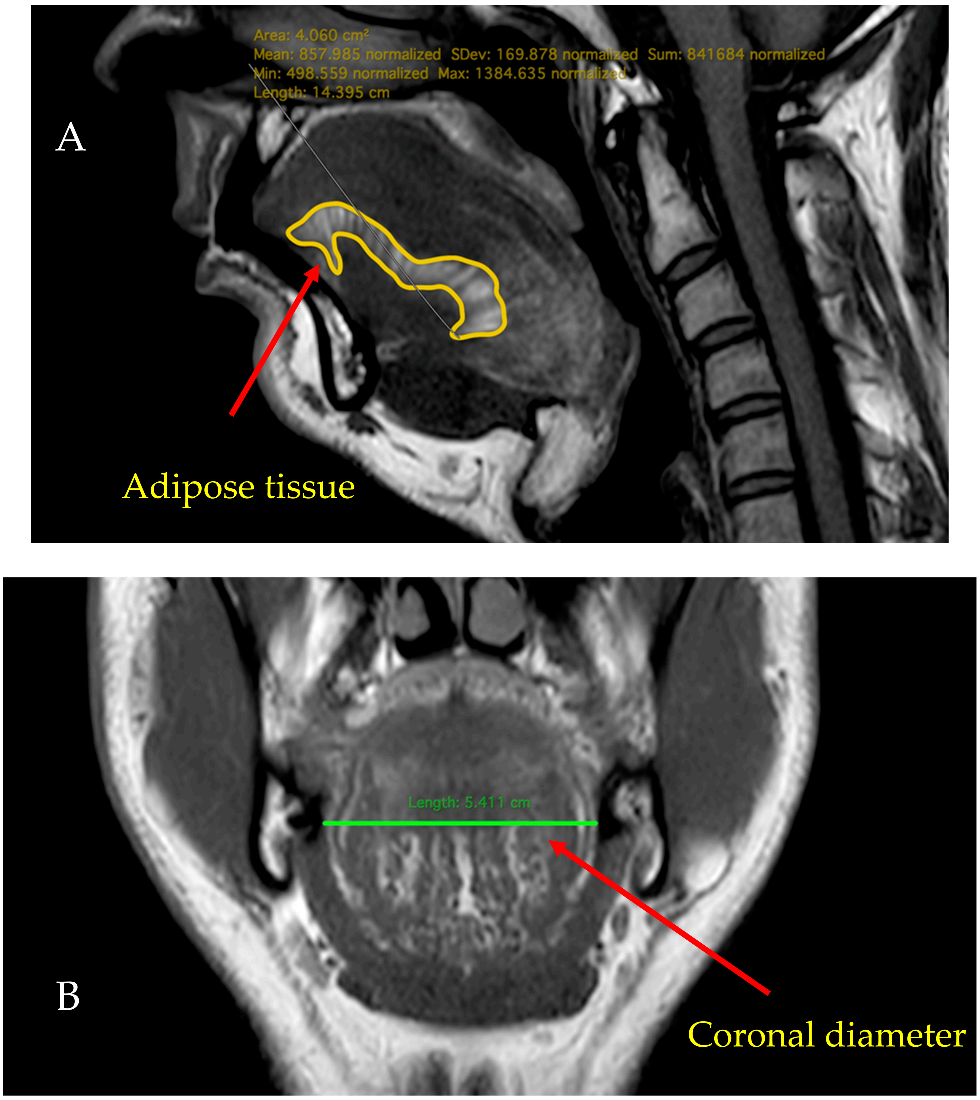


Figure 2. *Cont.*

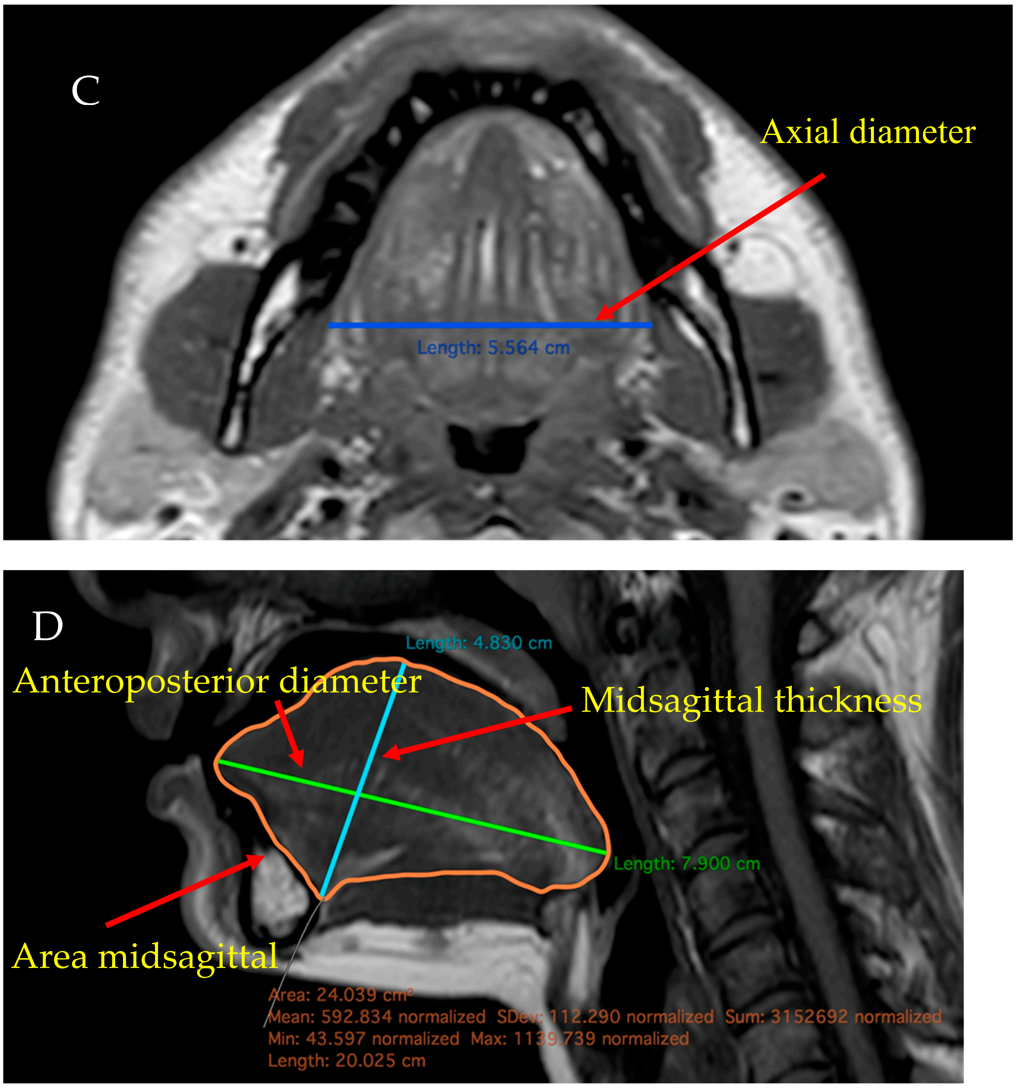


Figure 2. (**A**,**D**) sagittal, (**B**) coronal, (**C**) axial T1 TSE MRI scans showing the anteroposterior, axial, coronal, sagittal, and midsagittal diameters, and also the calculation of Fat% (taken from our data).

3. Results

3.1. Examination of the Tongue (US and MRI) Based on the AHI Categorisation of Patinets with OSA

The US and MRI parameters, with the results of the anthropometric measurements and categorisation by the AHI, are summarised in Table 1.

In terms of age, gender, and BMI parameters, a significant difference was observed between the two groups (Table 1). It was also detected when the axial, coronal, and sagittal diameters in the OSA and control groups were contrasted, along with the tongue volume, at rest, and during the MM measured by US. The tongue diameters during the manoeuvre were also significantly different. Using MRI, the anteroposterior and coronal diameters, also with the midsagittal area and the tongue fat of the midsagittal area, differed significantly between the OSA and control groups.

3.2. Examination of the Tongue between the Two Genders in OSA

The US and MRI tongue parameters depending on the gender in the OSA group are shown in Table 2.

Table 1. Patients' basic demographic data and US and MRI results according to the AHI classification. The parameters show the mean ± SD values. *** indicates the significant difference at $p < 0.01$ level, whereas ** the significant difference at $p < 0.05$ level and * the significant difference at $p < 0.1$.

	Control Group (n = 36)	OSA Patients (n = 64)	*p*-Value
Gender (men/women)	21/15	53/11	0.000 ***
BMI (kg/m^2)	23.14 ± 3.87	30.99 ± 2.33	0.000 ***
Age (years)	38.13 ± 12.14	44.40 ± 10.90	0.000 ***
Tongue US measurements			
Coronal diameter (cm)	4.98 ± 0.58	5.25 ± 0.86	0.0565 *
Axial diameter (cm)	4.65 ± 0.70	4.99 ± 0.91	0.0058 ***
Sagittal diameter (cm)	7.20 ± 0.75	7.33 ± 1.12	0.0225 **
Volume (cm^3)	45.27 ± 12.08	52.36 ± 15.52	0.0001 ***
Coronal diameter during MM (cm)	4.88 ± 0.66	5.19 ± 0.55	0.0029 ***
Axial diameter during MM (cm)	4.73 ± 0.67	5.06 ± 0.67	0.0063 ***
Sagittal diameter during MM (cm)	6.65 ± 0.57	6.90 ± 0.73	0.0579 *
Volume during MM (cm^3)	40.24 ± 8.09	47.48 ± 9.24	0.0000 ***
Tongue MRI examinations			
Anteroposterior diameter (cm)	7.127 ± 0. 66	7.665 ± 0.643	0.000 ***
Coronal diameter (cm)	4.57 ± 0.48	4.84 ± 0.45	0.006 ***
Volume (cm^3)	58.82 ± 13.18	67.00 ± 12.54	0.137
Area midsagittal (cm^2)	25.23 ± 3.69	28.06 ± 3.3	0.001 ***
Fat midsagittal (cm^2)	8.45 ± 1.72	9.19 ± 1.63	0.036 **
Tongue fat %	33 ± 4.00	33 ± 5.00	0.618

Table 2. US and MRI parameters of the tongue in male and female patients. Parameters show the mean ± SD values. * indicates the significant difference at $p < 0.1$ Only significantly different parameters are shown in the table.

	Gender		
	Men (n = 53)	**Women (n = 11)**	***p*-Value**
	Tongue US examinations		
Axial diameter during MM (cm)	5.13 ± 0.67	4.74 ± 0.62	0.0749 *
Volume (cm^3)	53.96 ± 15.88	44.64 ± 11.28	0.0697 *
Volume during MM (cm^3)	48.41 ± 9.39	42.99 ± 7.24	0.0769 *
	Tongue MRI examinations		
Coronal diameter (cm)	4.96 ± 0.40	4.32 ± 0.28	0.0798 *

In male patients, significantly higher tongue volumes were measured using US at rest and during MM, and axial diameters value were observed during MM. Of the MRI parameters, only the coronal diameters differed significantly between the genders.

The correlation between the men's and women's MRI parameters of the tongue and AHI is shown in Table 3. Different sample sizes can explain the differences in the set significance level.

Table 3. Stochastic relationship between MRI parameters and AHI in male and female patients. Parameters show the r^2 (determination coefficient) values. *** indicates the significant difference at $p < 0.01$ level, whereas ** the significant difference at $p < 0.05$ level and * the significant difference at $p < 0.1$. (l): linear estimation, (s): sigmoid estimation.

Independent Variables	Gender	
	Men (n = 74)	**Women (n = 26)**
MRI Tongue Parameters	r^2	r^2
Anteroposterior diameter (cm)	0.133 * (l)	0.073 (l)
Sagittal diameter (cm) (s)	0.050 * (s)	0.059 (l)
Axial diameter (cm) (l)	0.039 ** (l)	0.063 (l)
Coronal diameter (cm) (l)	0.073 ** (l)	0.015 ** (l)
Volume (cm^3) (l)	0.149 *** (l)	0.196 ** (s)
Area midsagittal (cm^2) (l)	0.186 *** (l)	0.192 ** (s)
Fat midsagittal (cm^2) (l)	0.043 (l)	0.428 *** (s)
Fat% (l)	0.001 (l)	0.260 *** (s)

The correlation between AHI and MRI parameters is remarkably different, based on the different numbers of male and female patients examined and the differences in the standard deviations (Table 3). When possible, linear estimations were applied, and sigmoid estimation was only used in the cases when a better outcome using sigmoid curves was suspected. According to the analysis, all MRI parameters were significantly correlated between the women's tongue parameters and AHI. The strongest correlation was observed in the case of the tongue volume, midsagittal area of the tongue, midsagittal fat of the tongue, and tongue fat% in the female participants, while the volume of the tongue, midsagittal area of the tongue and anteroposterior diameter in males. Although, in female patients, the $r^2 = 0.558$ determination coefficient was detected between BMI and AHI, which is stronger than in the case of males ($r^2 = 0.194$). However, significant correlations were observed independently of the determination coefficients in more than 99.9% of the cases.

3.3. Influence of Age on the Tongue Parameters in OSA

Table 4 shows the MRI parameters of the tongue depending on the OSA participants' age.

Table 4. MRI parameters of the tongue depending on age. The parameters show the mean $\pm$ SD values. *** indicates the significant difference at $p < 0.01$ level, whereas ** the significant difference at $p < 0.05$ level. Only the significantly different parameters are shown in the table.

	Age (Years)		
Tongue Parameters	**Age $\leq$ 40 (n = 21)**	**Age > 40 (n = 43)**	***p*-Value**
Anteroposterior diameter (cm)	7.83 ± 0.67	7.58 ± 0.62	0.0001 ***
Axial diameter (cm)	4.83 ± 0.49	4.71 ± 0.54	0.0165 **
Coronal diameter (cm)	4.99 ± 0.48	4.78 ± 0.43	0.000 ***
Volume (cm^3)	69.79 ± 13.85	65.64 ± 11.77	0.000 ***
Area midsagittal (cm^2)	28.71 ± 3.72	27.73 ± 3.06	0.000 ***

As presented in Table 4, none of the US parameters of the tongue were significantly influenced by the participants' age. Using MRI, patients with OSA under 40 years of age had significantly higher values of AP, axial and coronal diameters, tongue volume and midsagittal area.

3.4. Influence of BMI on the Tongue Parameters in OSA

The effect of BMI on the tongue MRI parameters is shown in Table 5.

Table 5. MRI parameters of the tongue depending on BMI values. Parameters show the mean ± SD values. ** indicates the significant difference at $p < 0.05$ level and * the significant difference at $p < 0.1$ Only the significantly different parameters are shown in the table.

Tongue Parameters	BMI (kg/m^2)			
	Normal [A] (n = 5)	Overweight [B] (n = 24)	Obese [C] (n = 35)	*p*-Value
Anteroposterior diameter (cm)	6.97 ± 0.40	7.68 ± 0.58	7.75 ± 0.66	0.0365 ** [A–C]
Sagittal diameter (cm)	4.92 ± 0.26	5.01 ± 0.38	5.27 ± 0.48	0.0366 ** [A–C]
Volume (cm^3)	57.60 ± 9.90	64.94 ± 10.58	69.76 ± 13.42	0.0738 * [A–C]
Area midsagittal (cm^2)	25.05 ± 1.76	27.72 ± 2.97	28.70 ± 3.45	0.054 * [A–C]

As Table 5 reveals, BMI has not significantly influenced any of the parameters of the US tongue in the OSA group. In the case of MRI parameters, obese patients with OSA had significantly higher AP and sagittal diameters, along with values of tongue volume and midsagittal area values.

3.5. Effects of BMI on the US and MRI Parameters of the Tongue in Male and Female Patients

Table 6 and Figure 3 summarises the effects of BMI on the men's and women's tongue parameters. The figure shows the estimated values by a red line. The dark red interval shows the 95% confidence band for the fitted function. This gives information on how well the values of the fitted function at particular values of the independent variable fall into the given interval. The interval of prediction is indicated by light red shading. This shows the interval where any arbitrary estimated value will fall with 95% probability if the calculations are repeated with any value of the independent variable.

In this case, our analyses were based on linear and sigmoid estimations. Although a better matching was observed in the case of the sigmoid estimation, the linear model was applied due to simplicity (Occam's Razor) [10].

A stronger correlation based on r^2 values was detected both in the case of US and MRI, although a lower number of female participants were examined (Table 6 and Figure 3). The strongest correlation between BMI and US parameters was observed in the case of axial and sagittal diameter and tongue volume during MM in male patients. For women, coronal and axial diameters, tongue volume, and coronal diameter during MM were detected to correlate more strongly with BMI. In the case of MRI parameters, the AP, sagittal, and coronal diameters, and tongue volume showed the strongest correlation. The tongue-based obstruction did not correlate with the AHI and BMI parameters, respectively.

3.6. Prediction of OSA and Tongue-Based Obstruction

The precision of the algorithm to detect patients with OSA, based on MRI and US measurements of the tongue, is summarised in Table 7. Prediction of tongue-based obstruction using USA measurements is presented in Table 8.

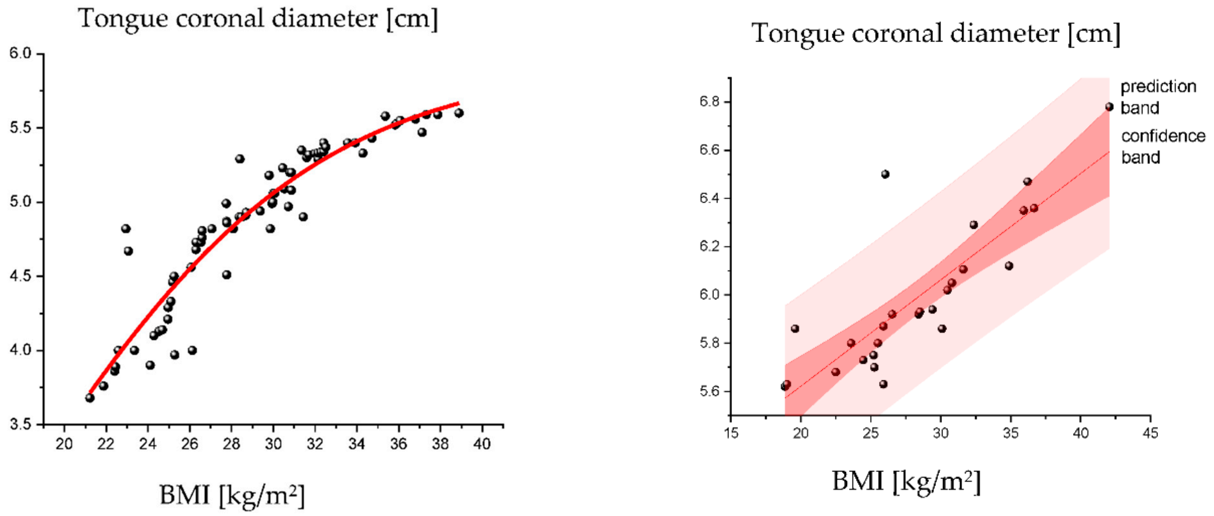
The results of the algorithm indicate that the tongue parameters can be helpful in categorising patients with OSA and tongue-based obstruction (Table 7). The sensitivity of the algorithm in the prognostication of OSA was defined as 84% for US, 79% for MRI, and 91% specificity for both methods, using quadratic discriminant analysis. No significant differences were detected between the specificities and sensitivities of the two methods in diagnosing patients with OSA. However, in the classification of obstruction, the sensitivity differed significantly (94% for US and 56% for MRI). The US has given a false OSA diagnosis in 9%, while MRI in 18%. To detect the possible location of the obstruction, the US imaging result was incorrect in 11% of cases, whereas the MRI results were incorrect in 13%.

Table 6. Correlation between BMI (as an independent variable) and the US and MRI parameters of the tongue (as dependent variables) in male and female patients. Parameters show the r^2 (determination coefficient) values *** indicates the significant difference at $p < 0.01$ level, (l) linear estimation and (s) sigmoid estimation. Independent variable: BMI, dependent: tongue parameters.

Dependent Variables	Gender	
	Men (n = 74)	**Women (n = 26)**
US tongue parameters	**r2**	**r2**
Coronal diameter (cm)	0.28 ***	0.7 ***
Axial diameter (cm)	0.31 ***	0.75 ***
Sagittal diameter (cm)	0.30 ***	0.62 ***
Volume (cm^3)	0.32 ***	0.69 ***
Coronal diameter during MM (cm)	0.29 ***	0.71 ***
Axial diameter during MM (cm)	0.33 ***	0.59 ***
Sagittal diameter during MM (cm)	0.35 ***	0.55 ***
Volume during MM (cm^3)	0.34 ***	0.5 ***
MRI tongue parameters	**r^2**	**r^2**
Anteroposterior diameter (cm)	0.328 ***	0.73 ***
Sagittal diameter (cm) (s)	0.32 ***	0.77 ***
Axial diameter (cm) (l)	0.33 ***	0.65 ***
Coronal diameter (cm) (l)	0.37 ***	0.72 ***
Volume (cm^3) (l)	0.41 ***	0.712 ***
Area midsagittal (cm^2) (l)	0.42 ***	0.463 ***
Fat midsagittal (cm^2) (l)	0.422 ***	0.410 ***
Fat% (l)	0.241 ***	0.253 ***

Table 7. Prognosis of tongue-based obstruction and OSA, according to US and MRI measurements (quadratic discriminant analysis).

	Location of the Obstruction		**OSA**	
	Categorisation Based on Anthropometric Data		**Categorisation Based on Anthropometric Data**	
	US Parameters	**MRI Parameters**	**US Parameters**	**MRI Parameters**
True-positive	27	27	34	47
True-negative	62	60	57	35
False-positive	5	7	2	1
False-negative	6	6	7	17
Correct categorisation	89%	87%	91%	82%
False categorisation	11%	13%	9%	18%
Sensitivity	0.84	0.79	0.94	0.56
Specificity	0.91	0.91	0.89	0.92



The correspondence between BMI and the tongue volume during MM in men (linear curve)

The correspondence between BMI and the tongue volume during MM in women (linear curve)

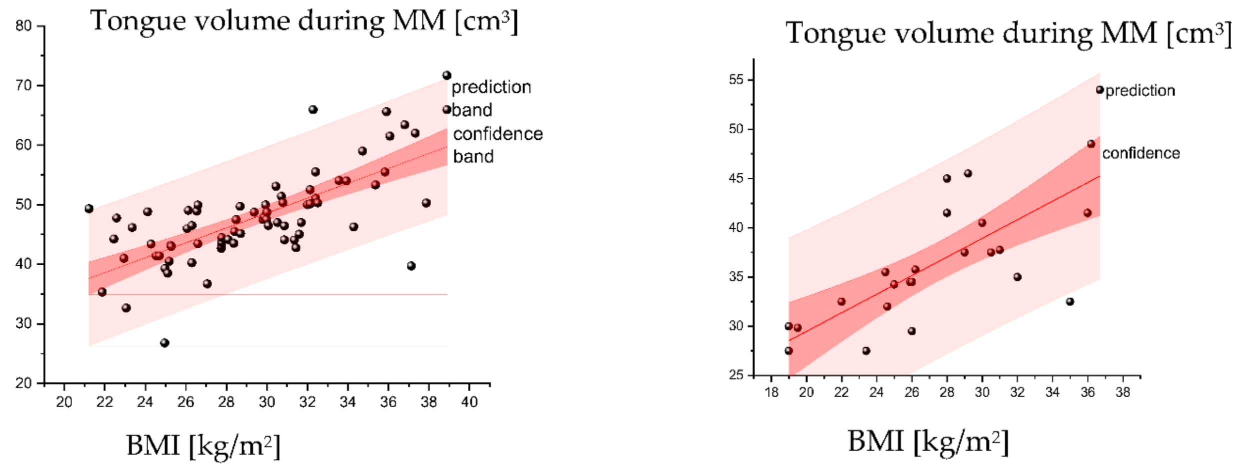


Figure 3. Correlation between BMI and the coronal diameter of the tongue using US and tongue volume during MM in male and female patients.

Table 8. A prediction of tongue-based obstruction using tongue US parameters and anthropometric parameters by the quadratic discriminant analysis.

Real Obstruction	Estimated Obstruction			
	No Obstruction	Partial Obstruction	Total Obstruction	Correct Categorisation
No obstruction	24	5	5	70.6%
Partial obstruction	5	21	6	65.6%
Total obstruction	3	5	26	76.5%

As Table 8 reveals, using US measurements, analysed by the quadratic discriminant analysis, we were able to perform a correct categorisation in 71%. The algorithm correctly categorised the absence of tongue-based obstruction in 70.6%, partial obstruction in 65.6%, and total obstruction in 76.5% of cases.

4. Discussion

One of the main objectives of the present study was to analyse the effects of age, sex, and BMI on the tongue parameters in OSA. Furthermore, the prognostication of OSA and tongue-based obstruction using US and MRI measurements were also analysed. The clinical significance of the current study is to screen for previously not diagnosed OSA cases and subjects with tongue-based obstructions who undergo US or MRI examinations with another indication (for instance, salivary gland problems, lymph node pathologies in the neck region, or thyroid gland abnormalities). Improving OSA diagnostic methods is vital due to the high number of undiagnosed cases.

MRI of the tongue can measure the parameters of the soft tissues in the coronal, axial, and sagittal planes. Moreover, three-dimensional reconstructions and determination of the volume of cross-sectional area are also possible [11]. In our studied population, MRI only showed a significantly different result for OSA patients in the case of coronal and anteroposterior diameters, midsagittal area, and fat of the midsagittal area parameters, compared to the control group. Do et al. found higher tongue volume values in the OSA group, although the difference was insignificant compared to the non-OSA group [12]. These findings are in contrast to the results of Turnbull et al. and Iida-Condo et al., who have observed significant differences [13,14]. Based on our results, Fat% did not differ significantly; however, Kim et al. concluded significant differences also with a correlation between AHI, Fat%, and tongue volume [15].

The correlation between US and MRI diameters and volumes is weak, since US is a subjective method, and there are also differences between the US and MRI parameters calculated by the different imaging softwares. Moreover, the amorphous form of the tongue also makes it difficult to calculate the parameters correctly.

US measurements of the tongue were also observed during MM to detect possible changes in the volumes and diameters of the tongue. The effectiveness of MM is questionable in the diagnosis of OSA. Although some authors have not found a significant correlation between obstructions during MM and the results of sleep endoscopy [16], others have observed significant correspondences between multilevel hypopharyngeal obstructions and Epworth Sleepiness Scale values [17]. Gregório et al. have detected more retroglossal obstruction during sleep-endoscopy than in the case of MM [18]. Huang et al. have not found a correlation between the severity of obstruction, AHI, BMI, oxygen saturation values, and MM [19]. Using US, significantly higher diameters and tongue volumes were detected in patients with OSA, both at rest and during MM, compared to the control group. Shu et al. examined US and found higher tongue thicknesses in the coronal plane of those involved in OSA, similarly to our findings [20]. Chen et al. concluded that the thickness of the tongue base measured by the US during MM is an essential indicator for OSA severity [21]. Manlises et al. detected significantly higher tongue values during MM [22]. Our results did not show a significant correspondence between tongue obstruction detected by sleep endoscopy and tongue volumes during MM, using US measurements. Therefore, MM is unable to detect tongue-based obstructions.

It is a well-known fact that the patients’ age, sex, and nutritional status significantly influence on the pathogenesis of OSA [1]. Therefore, the effects of these parameters were also investigated. The effect of gender was observed on all US parameters, although a significant difference was only detected in the case of tongue volume during normal breathing and MM and axial tongue diameter during MM. Using MRI, only the diameter of the coronal tongue diameter in male patients differed, in contrast to other investigations, which have observed significantly higher volumes of the tongue and of the cross-sectional area parameters in men [13,23–25]. Based on our results, a significant correlation was detected between male and female patients concerning BMI and US tongue parameters, with a stronger correlation in the case of females. AHI and BMI values also showed a stronger correlation in women. However, it can also be concluded that the correlation between AHI and BMI parameters was significant in all cases. A strong correlation was detected between men’s and women’s MRI and AHI parameters. Although fewer women were enrolled, the correlation was defined as significant. Finally, it can be concluded that female patients had significantly lower values of tongue parameters, and these parameters were stronger correlated with AHI and BMI parameters, as in the case of male subjects. Therefore, in addition to the parameters of the tongue and BMI, other factors, for example age and central type of obesity, are also essential in the pathogenesis of OSA in men, in contrast to women.

In the present investigation, the US parameters were not influenced by the participants' age, but in the MRI examinations, most of the parameters showed significantly higher values in the group of patients under 40 years of age. This finding can be explained by the younger OSA patients' (i.e., under 40 years) higher BMI and AHI values.

No influence of nutritional status on US parameters was detected, BMI and tongue volume were not strongly correlated since the inaccuracy for US measurements is well known, and according to Gauss's law of error propagation [26], multiple inaccuracies of measurements can be observed in the case of tongue volume, determined by tongue parameters. However, significantly higher anteroposterior sagittal diameters, tongue volume, and midsagittal area parameters were shown in obese patients using MRI. Similar to our results, Do et al. have also found a significant correlation between tongue volume and BMI [12]. However, our results have shown significant differences between BMI, US, and most MRI parameters in the OSA and control groups. In the OSA group, obese patients had significantly higher tongue volumes by MRI, although the Tongue Fat % and Tongue Fat midsagittal parameters did not differ significantly. Although obesity is a significant risk factor for OSA, no correlation was observed between tongue fat tissue and OSA. This contrasts with previous results, which have indicated correlations between tongue fat and sleep-related breathing disorders [27,28].

In the current study, our objective was to analyse the presence of OSA and tongue-based obstruction, using US and MRI and machine learning methods for data processing. The sensitivity and specificity of the applied algorithm, which included some anthropometric parameters in addition to the values of the US and MRI values, were different in the case of the two medical imaging methods. In the prognosis of OSA, a US sensitivity of 94% was detected, preceding the MRI sensitivity (56%). However, a similar specificity for the two methods was observed (89% for US and 92% for MRI). The US could detect tongue-based obstruction with an 84% sensitivity, and so was MRI with 79%. In the location of tongue-based obstruction, US and MRI showed similar results in specificity (91%).

The algorithm based on quadratic discriminant analysis was correct in the prognosis of the presence of OSA in 91% using US and 82% applying MRI. We correctly detected tongue-based obstruction in 89% and by MRI in 87%. Tongue-based obstruction severity (i.e., no, partial or total obstruction) could be observed using US in 71%.

To our knowledge, it is the first study that has analysed the role of US and MRI examinations in the prognosis of OSA and tongue-based obstruction and the effects of age, sex, and BMI on the tongue parameters in patients with OSA. US examinations can detect the possible background of OSA using a relatively inexpensive and safe method, which can be easily applied even in an outpatient setting. Although OSA screening is possible, for example, by using questionnaires or screening devices, it can be stated that independently of the indication of US or MRI examinations, these methods give another possibility of screening for OSA patients who were previously not diagnosed with OSA or had OSA symptoms, also observed in previous studies [21,28]. Additionally, examination of tongue-based obstruction using US can be helpful in therapy planning.

However, our investigation has some limitations. Still, the categorisation of the participants based on multivariate methods was highly effective, and the sensitivity tests of the models have shown that the actual data makes it possible to categorise OSA. However, more subjects have to be examined to give the possibility of dividing OSA into different severity categories. The US and MRI examinations were carried out in awake subjects; therefore, they do not present anatomical situations during sleep. This is particularly essential as Huang et al. have observed a stronger correlation between AHI and tongue base thickness during drug-induced sleep than in awake participants, using US measurements [19]. When MM was applied, the barometry of the pharynx was not used; therefore, MM was not performed in a standardised way. The volumes of the tongue determined by US between the various nutritional status groups did not differ, which can significantly limit the usability of the data. Polysomnography at night was used; therefore, night-to-night variability in OSA severity could have influenced the correlations between OSA severity and the results of medical imaging measurements. The tongue Fat% calculation is not precise since tongue Fat% is an estimated value.

5. Conclusions

Our results highlight that in addition to the wide indication of US and MRI examination in everyday clinical practice, the presence of OSA and tongue-based obstruction can also be predicted, including anthropometric parameters. The algorithm created can predict the presence of OSA and tongue-based obstruction with high precision. These results can especially be significant in those cases where US or MRI examinations are used with another indication than the diagnosis of OSA in patients with previously not diagnosed OSA. Therefore, their diagnostic process can begin.

The influence of age, gender, and BMI values on the tongue parameters is highly complex. Since a better correlation was observed between the women's parameters of the tongue, AHI, and BMI, this fact can indicate the importance of these parameters in the case of women. For male patients, other factors are also of great importance. MM was not defined as a reliable examination to detect tongue-based obstruction.

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