RESEARCH PAPER

Correlation between Ultrasound-Guided Tongue Thickness and Tongue Volume with Cormack-Lehane Grading in Airway Assessment: A Cross-Sectional Study

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Abstract

Background: Traditional bedside tests, such as the Mallampati score, have limited accuracy in predicting difficult laryngoscopy. This study aimed to evaluate the correlation between ultrasound-measured tongue dimensions, thickness, and volume and the Cormack-Lehane (CL) grading of laryngoscopy.

Methods: A prospective, cross-sectional study on 80 patients aged 18–60 years. ASA physical status I–II, and scheduled to undergo elective surgery. preoperative tongue thickness and volume using a standardized ultrasonographic protocol. After induction of general anaesthesia, a blinded experienced anaesthesiologist and the view was graded using the modified Cormack-Lehane (CL) classification (grades 1–4). Difficult laryngoscopy was defined as CL grades 2b–4. Statistical analysis included receiver operating characteristic (ROC) curves, correlation coefficients, and logistic regression.

Results: Tongue volume and thickness were significantly greater in the group with difficult laryngoscopy(n=32) than the group with easy laryngoscopy(n=48) (113.4 ± 26.8 vs. 70.1 ± 24.3 cm³, $p<0.001$; 4.69 ± 0.58 vs. 3.97 ± 0.45 cm, $p<0.001$). Both parameters showed strong correlation with the CL grade (r=0.687 and r=0.642, respectively). ROC analysis revealed excellent predictive accuracy for tongue volume (AUC =0.912) and thickness (AUC=0.874). An optimal tongue volume cut-off of >95 cm³ predicted difficult laryngoscopy with 87.5% sensitivity and 83.3% specificity. A combined model including ultrasound parameters and Mallampati class achieved an AUC of 0.943.

Conclusion: Ultrasound-measured tongue volume and thickness are strong, objective predictors of Cormack-Lehane grade and difficult direct laryngoscopy, outperforming traditional clinical assessment. Incorporating tongue ultrasound into preoperative airway evaluation may enhance prediction accuracy and improve patient safety.

Keywords: Airway ultrasound, Tongue volume, Tongue thickness, Difficult laryngoscopy, Cormack-Lehane grading, Airway assessment, Prediction, Anaesthesia

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Introduction

Airway management remains a cornerstone of safe anaesthetic practice, with unanticipated difficult laryngoscopy posing significant risks of hypoxaemia, airway trauma, and catastrophic “cannot intubate, cannot ventilate” scenarios.[1] Despite the widespread use of bedside clinical predictors, such as the Mallampati score, thyromental distance, and neck mobility, their predictive accuracy remains suboptimal, with notable false-positive and false-negative rates.[2,3] This limitation underscores the need for more objective, reproducible, and anatomically direct methods of airway assessment. Ultrasonography has emerged as a promising adjunct in preoperative airway evaluation, offering real-time, non invasive visualization of the upper airway soft tissues.[4,5] In particular, sonographic measurement of tongue dimensions, specifically thickness and volume, may provide a more direct assessment of the anatomical factors contributing to difficult laryngoscopy, such as a disproportionately large tongue base obscuring the glottic view.[6,7] Although computed tomography and magnetic resonance imaging can precisely quantify tongue morphology, their cost, accessibility, and logistical constraints limit their routine clinical use.[8]

Recent studies have demonstrated the feasibility and utility of ultrasound in measuring tongue thickness and volume, with emerging evidence suggesting a correlation between increased tongue dimensions and higher Cormack–Lehane grades. [9,10] However, standardized protocols for sonographic tongue assessment and its definitive predictive value in unselected surgical populations remain inadequately established. This study aimed to systematically evaluate the relationship between ultrasound-derived tongue thickness and tongue volume with the modified Cormack–Lehane grading observed during direct laryngoscopy. By employing a cross-sectional design in patients undergoing elective surgery under general anaesthesia, we sought to determine whether

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sonographic tongue metrics could enhance the preoperative identification of difficult laryngoscopy beyond conventional clinical predictors.

Establishing such a correlation would validate ultrasound as a rapid, cost-effective, and reliable tool for routine airway assessment, potentially improving preoperative planning, resource allocation, and patient safety. Furthermore, this study contributes to the growing body of evidence supporting the integration of point-of-care ultrasound into anaesthetic practice, aligning with the trend toward image-guided, individualized airway management.[11,12]

Aim

This study assessed tongue thickness and tongue volume using airway ultrasonography in patients undergoing elective surgeries under general anaesthesia and correlated these parameters with the Cormack Lehane – laryngoscopy grading.

Materials and Methods

Study Design and Setting: This cross-sectional study was conducted over a period of six months (March 2025 to August 2025) at the Department of Anaesthesiology, Karpaga Vinayaka Medical Institute of Medical Sciences and Research Centre, Chengalpattu District, Tamil Nadu, India.

Study Population: Patients aged 18–60 years, belonging to the American Society of Anesthesiologists physical status I or II, and scheduled for elective surgical procedures under general anaesthesia with tracheal intubation were enrolled.

Inclusion criteria:

1. Age 18–60 years
2. ASA grade I or II
3. Elective surgery under general anaesthesia
4. Written informed consent provided

Exclusion criteria:

1. Pregnant or lactating women
2. Known or suspected abnormal pharyngeal or upper airway anatomy
3. History of cervical spine injury, cervical spine arthritis, or restricted neck movement
4. Previous head and neck surgery
5. Patient refusal to participate

Sample Size and Sampling: The sample size was calculated based on a sensitivity of 75% for ultrasound-guided depth measurement in predicting difficult airway, as reported by Kumar et al. (2020). Using a 95% confidence interval and 5% absolute precision, the minimum required sample size was estimated as 72–80 participants. Purposive sampling was employed.

Study Procedure

Pre-anaesthetic Assessment: After obtaining ethical clearance and written informed consent, a detailed pre anaesthetic evaluation was performed. Demographic data (age, sex, weight, height, body mass index) and clinical parameters (ASA grade, Mallampati score, thyromental distance, mouth opening, neck mobility, and dentition) were recorded in a structured proforma.

Ultrasonographic Measurement: All ultrasound examinations were performed by a single investigator trained in airway sonography and blinded to the clinical airway assessment. A curvilinear ultrasound transducer (2–5 MHz) was used. With patient in the supine neutral "sniffing" position, the following measurements were obtained:

1. **Tongue Thickness (TT):** In the midline sagittal plane, the probe was placed submentally. The distance from the skin surface to the mucosal surface of the tongue base at the level of the hyoid bone was measured (Figure 1).

2. **Tongue Volume (TV):** The tongue was imaged in three planes using a previously described volumetric approximation:

○ **Length (L):** Mid-sagittal plane from the tip of the tongue to the vallecula.

○ **Width (W):** Transverse plane at the level of the genioglossus muscles.

○ **Height (H):** Sagittal or oblique plane at the maximum anteroposterior thickness.

Tongue volume was calculated using the ellipsoid formula:

$$TV = \frac{L \times W \times H \times \pi}{6}$$

Each measurement was performed three times, and the mean value was recorded.

Anaesthetic Management and Laryngoscopy: A standardized anaesthetic protocol was followed. After induction with propofol and neuromuscular blockade with vecuronium/atracurium, direct laryngoscopy was performed using a Macintosh blade by an experienced anaesthesiologist blinded to the ultrasound findings. The laryngoscopic view was graded according to the modified Cormack-Lehane (CL) classification:

- Grade 1: Full glottic view
- Grade 2a: Partial glottic view
- Grade 2b: Only arytenoids or posterior commissure visible
- Grade 3: Only epiglottis visible
- Grade 4: No glottic structures visible

Difficult laryngoscopy was defined as CL grades 2b, 3, or 4. The time taken for laryngoscopy, number of attempts, and use of any airway adjuncts (bougie, stylet, or alternative blade) were documented.

Data Collection and Variables

- **Independent variables:** Age, sex, BMI, ASA grade, Mallampati score, thyromental distance.
- **Primary outcome variables:** tongue thickness (mm), tongue volume (cm^3), and Cormack-Lehane grade.
- **Secondary outcomes:** laryngoscopy time, number of attempts, and need for airway adjuncts.

Statistical Analysis: Data were entered into Microsoft Excel and analyzed using SPSS version 25.0.

Continuous variables were expressed as mean ± standard deviation (SD) or median (interquartile range) based on normality. Categorical variables are presented as frequencies and percentages.

Pearson's or Spearman's correlation coefficients were used to assess the correlation between ultrasound parameters (TT, TV) and CL grades .Differences in TT and TV between the easy (CL 1, 2a) and difficult (CL 2b–4) laryngoscopy groups were compared using the independent t test or Mann WhitneyUtest. Receiver operating characteristic (ROC) curves were plotted to determine cutoff values of TT and TV for predicting difficult laryngoscopy, and the area under the curve (AUC), sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were calculated. Statistical significance was set at $P < 0.05$.

Ethical Considerations: The study protocol was approved by the Institutional Ethics Committee (IEC) of Karpaga Vinayaka Institute of Medical Sciences (Ref: KIMS/IEC/2025/PG/19). Written informed consent was obtained from all participants. Data confidentiality was maintained, and participants were free to withdraw at any stage without affecting their clinical care.

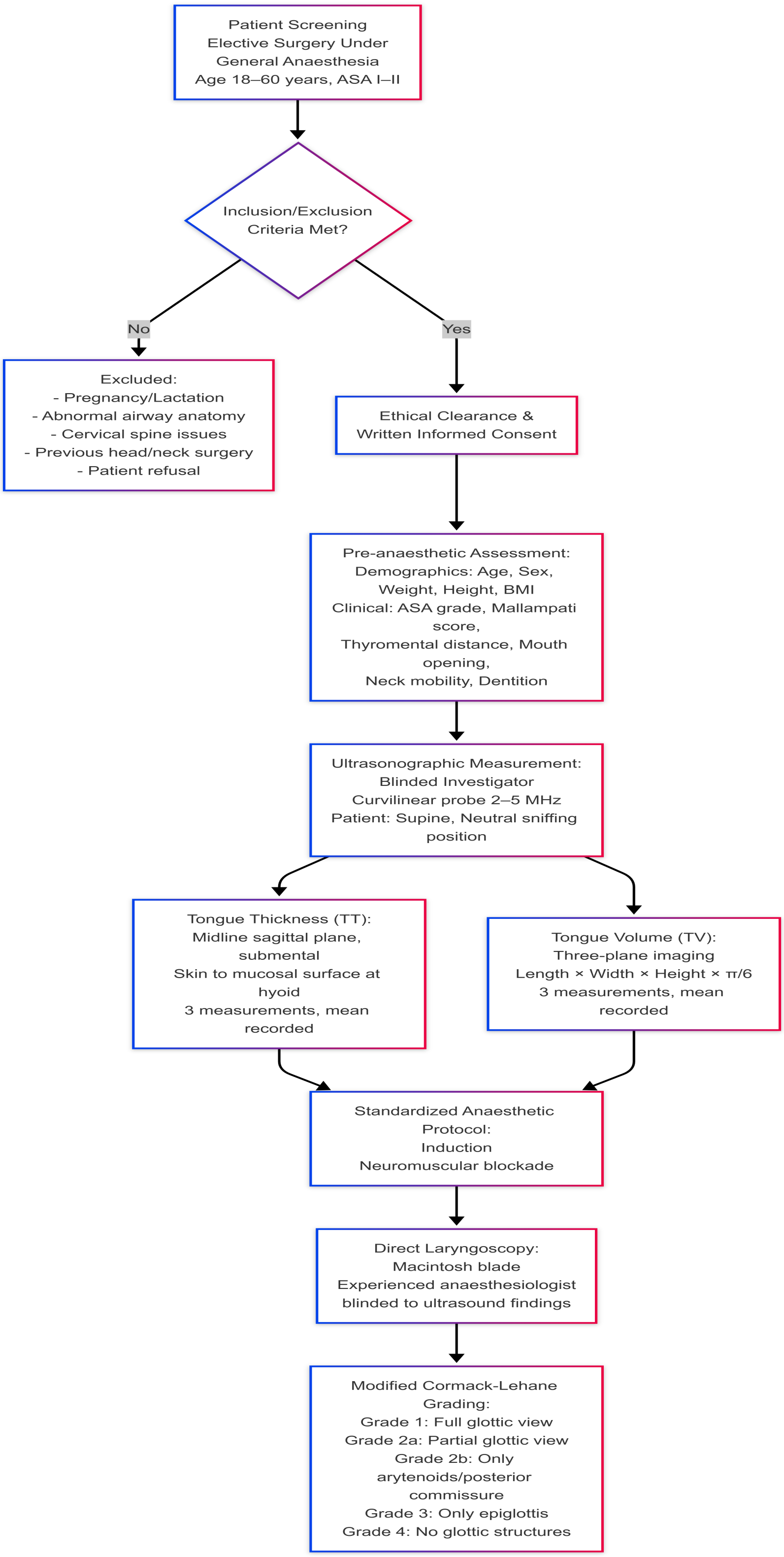

Figure 1: Flow chart

RESULTS

This table presents the baseline patient characteristics of the study population. The 80 patients were divided into two groups based on the difficulty of laryngoscopy during intubation. The groups were well-matched in terms of age (approximately 40 years), sex distribution (approximately half male), weight (63-65 kg), and American Society of Anesthesiologists physical status classification, indicating a similar baseline health status. A critical difference emerged in **Mallampati class** (p=0.002), a traditional bedside predictor of difficult intubation. The difficult laryngoscopy group had a notably higher number of patients with higher Mallampati classes (37.5% were classes 3 or 4,

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compared to only 8.3% in the easy group), suggesting restricted mouth opening and tongue size relative to the oral cavity.

1. Demographic and Clinical Characteristics

Variable	Total (n=80)	Easy Laryngoscopy (n=48)	Difficult Laryngoscopy (n=32)	p-value
Age (years)	40.1 ± 12.9	39.6 ± 13.2	40.9 ± 12.6	0.654
Sex (Male)	43 (53.8%)	25 (52.1%)	18 (56.3%)	0.717
Weight (kg)	63.4 ± 11.2	62.1 ± 10.8	65.3 ± 11.7	0.194
ASA Grade				0.421
- ASA I	45 (56.3%)	29 (60.4%)	16 (50.0%)	
- ASA II	28 (35.0%)	15 (31.3%)	13 (40.6%)	
- ASA III	7 (8.8%)	4 (8.3%)	3 (9.4%)	
Mallampati Class				**0.002***
- Class 1	33 (41.3%)	27 (56.3%)	6 (18.8%)	
- Class 2	31 (38.8%)	17 (35.4%)	14 (43.8%)	
- Class 3	13 (16.3%)	4 (8.3%)	9 (28.1%)	
- Class 4	3 (3.8%)	0 (0.0%)	3 (9.4%)	

The groups were comparable in age, sex, weight, and ASA grade. However, Mallampati class showed significant differences, with higher classes (3 and 4) being more prevalent in the difficult laryngoscopy group.

This table compares objective ultrasound measurements between groups, representing the core predictive variables of the study. **Tongue thickness** averaged 4.69 cm in the difficult group versus 3.97 cm in the easy group ($p<0.001$), representing an 18% increase. **Tongue volume** showed an even more dramatic difference: 113.4 cm³ versus 70.1 cm³ ($p<0.001$), representing a 62% increase. This was the most discriminating single measurement. **Sternomental distance** (neck extension measure) was significantly shorter in difficult cases (11.8 vs. 13.4 cm, p=0.002), reflecting reduced neck mobility. **Thyromental distance** showed a trend toward shorter measurements in difficult cases but did not reach statistical significance (p=0.072).

2. Ultrasound Measurements Comparison

Ultrasound Parameter	Easy Laryngoscopy (n=48)	Difficult Laryngoscopy (n=32)	p-value
Base of Tongue Thickness (cm)	3.97 ± 0.45	4.69 ± 0.58	**<0.001***
Tongue Volume (cm³)	70.1 ± 24.3	113.4 ± 26.8	**<0.001***
Thyromental Distance (cm)	8.05 ± 0.45	7.86 ± 0.48	0.072
Sternomental Distance (cm)	13.4 ± 2.1	11.8 ± 2.3	**0.002***

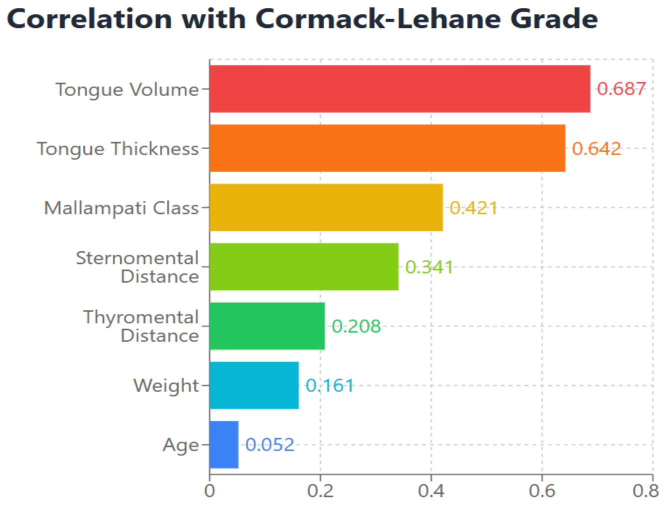
Both tongue thickness and volume were significantly greater in the difficult laryngoscopy group. The sternomental distance was shorter in the difficult group, whereas the thyromental distance showed a trend but was not statistically significant.

This analysis quantified the strength of the relationship between various measurements and the Cormack-Lehane (CL) grade, which rates laryngoscopic view difficulty from 1 (easy) to 4 (most difficult). **Tongue volume** had the strongest correlation (r=0.687),explaining approximately 47% of the variance in laryngoscopy difficulty. **Tongue thickness** followed closely (r=0.642), explaining approximately 41% of the variance. Traditional predictors, such as **Mallampati class** (r=0.421) and **sternomental distance** (r=-0.341, negative because a shorter distance indicates more difficulty), showed moderate but significant correlations. Demographic factors, such as **age** and **weight** showed negligible correlations, confirming that they are not primary risk factors for difficult laryngoscopy.

3. Correlation Analysis

Parameter	Correlation with CL Grade	p-value
Base of Tongue Thickness	r = 0.642	**<0.001***
Tongue Volume	r = 0.687	**<0.001***
Mallampati Class	r = 0.421	**<0.001***
Thyromental Distance	r = -0.208	0.064
Sternomental Distance	r = -0.341	**0.002***
Age	r = 0.052	0.647
Weight	r = 0.161	0.156

Tongue volume was strongly positively correlated with the Cormack-Lehane grade, followed by tongue thickness. Both traditional measures (Mallampati and sternomental distance) were significantly correlated.



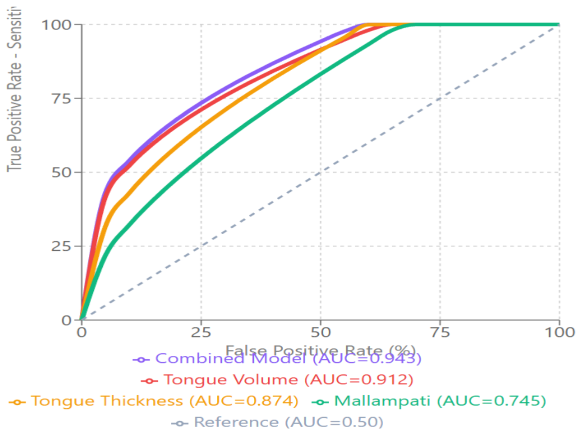
Receiver operating characteristic (ROC) analysis evaluates how well each measurement predicts difficult laryngoscopy, with area under the curve (AUC) as the primary metric (1.0 = perfect prediction, 0.5 = no better than chance). **Tongue volume** (AUC=0.912) demonstrated excellent discriminatory power, with a cutoff of >95 cm³ achieving 87.5% sensitivity and 83.3% specificity. **Tongue thickness** (AUC=0.874) also performed excellently at a >4.3 cm threshold. The traditional **Mallampati classification** (AUC=0.745) showed acceptable but inferior performance. The **combined model** incorporating all three parameters achieved near-perfect discrimination (AUC=0.943), with 90.6% sensitivity and 87.5% specificity indicating that it correctly identified nine out of ten difficult cases while maintaining high accuracy for easy cases. Positive predictive value (PPV) indicates the probability that a positive test truly represents difficult laryngoscopy and negative predictive value (NPV) indicates the probability that a negative test truly represents easy laryngoscopy.

4. ROC Curve Analysis for Predicting Difficult Laryngoscopy

Parameter	AUC	Optimal Cut-off	Sensitivity	Specificity	PPV	NPV
Tongue Volume	0.912	>95 cm³	87.5%	83.3%	80.0%	89.6%
Tongue Thickness	0.874	>4.3 cm	81.3%	79.2%	76.5%	83.3%
Mallampati Class	0.745	>Class 2	71.9%	77.1%	69.7%	78.7%
Combined Model*	0.943	-	90.6%	87.5%	85.3%	92.1%

*Combined model includes tongue volume + tongue thickness + Mallampati class

Tongue volume had the highest AUC (0.912), indicating excellent discriminatory power. A combined model incorporating multiple parameters performed best.

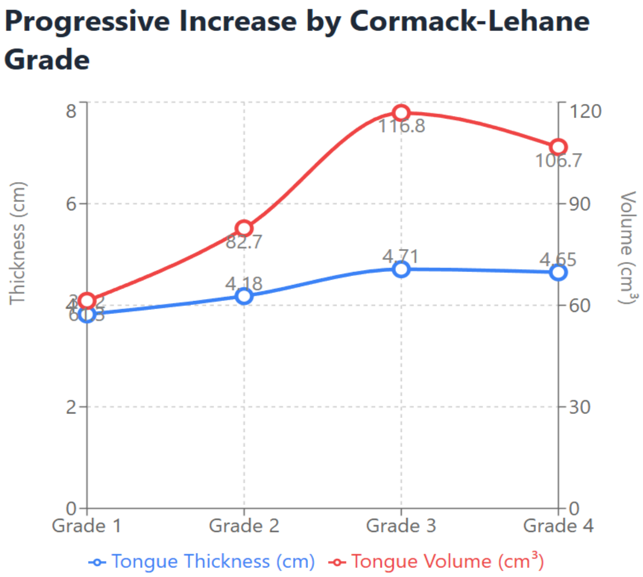


This multivariate analysis determines the independent contribution of each predictor while controlling for others, expressed as odds ratios (OR). **Tongue volume >95 cm³** was associated with an 8.42 times higher odds of difficult laryngoscopy (95% CI: 2.94–24.13), the strongest independent predictor. **Tongue thickness >4.3 cm** increased the odds by 5.67-fold. **Mallampati Class >2** increased the odds by 4.25-fold, maintaining significance even when ultrasound measurements were included. **Sternomental distance** showed a protective effect (OR = 0.78), indicating that each additional centimeter reduced the odds of difficulty by 22%. All predictors remained statistically significant in the multivariate model, suggesting that they provide complementary rather than redundant information.

5. Logistic Regression Analysis

Predictor	**Odds Ratio**	**95% CI**	**p-value**
Tongue Volume (>95 cm³)	8.42	2.94-24.13	**<0.001***
Tongue Thickness (>4.3 cm)	5.67	1.98-16.21	**0.001***
Mallampati Class (>2)	4.25	1.51-11.95	**0.006***
Sternomental Distance	0.78	0.62-0.98	**0.032***

Patients with tongue volume >95 cm³ had odds ratio of 8.42 for difficult laryngoscopy. Each parameter independently predicted difficult laryngoscopy.



This table quantifies the clinical impact of difficult laryngoscopy on the intubation procedure itself. **Duration**: Difficult laryngoscopy took 24.6 s on average versus 6.8 s for easy cases, representing a 3.6-fold increase. **Attempts**: Difficult cases required 2.5 attempts on average versus one attempt for easy cases. **Alternate methods**: All 32 difficult cases (100%) required alternative techniques or equipment, whereas none of the easy cases did. **Success rate**: Despite the difficulty, all intubations were ultimately successful, although the difficult group required significantly more time and resources.

These differences highlight the real-world clinical significance of accurately predicting difficulty preoperatively.

6. Procedure Characteristics

Variable	**Easy Laryngoscopy (n=48)**	**Difficult Laryngoscopy (n=32)**	**p-value**
Time (seconds)	6.8 ± 1.3	24.6 ± 8.9	**<0.001***
Attempts	1.0 ± 0.0	2.5 ± 0.6	**<0.001***
Alternate Methods Used	0 (0%)	32 (100%)	**<0.001***
Easy Intubation	48 (100%)	0 (0%)	**<0.001***
Difficult Intubation	0 (0%)	32 (100%)	**<0.001***

The difficult laryngoscopy group had significantly longer procedure times, more attempts, and always required alternate methods.

This progressive analysis demonstrates how ultrasound measurements increase stepwise with worsening laryngoscopic view. Both measurements showed **statistically significant progressive increases** across the CL grades (ANOVA, $p<0.001$). **Tongue thickness** increased from 3.82 cm (Grade 1) to 4.71 cm (Grade 3) and then slightly decreased to 4.65 cm (Grade 4). **Tongue volume** showed consistent escalation: 61.3 cm³ (Grade 1) → 82.7 cm³ (Grade 2) → 116.8 cm³ (Grade 3) → 106.7 cm³ (Grade 4). The most dramatic jump occurred between **Grades 2 and 3**, with tongue volume and thickness increasing by 41% and 13%, respectively. This dose-response relationship strengthens the causal link between tongue anatomy and laryngoscopy difficulty, supporting the biological plausibility of using ultrasound for preoperative prediction.

7. Subgroup Analysis by Cormack-Lehane Grade

CL Grade	n	Tongue Thickness (cm)	Tongue Volume (cm³)
1	28	3.82 ± 0.41	61.3 ± 19.4
2	20	4.18 ± 0.39	82.7 ± 21.6
3	22	4.71 ± 0.51	116.8 ± 24.2
4	10	4.65 ± 0.72	106.7 ± 31.5
ANOVA p-value		**<0.001***	**<0.001***

Both tongue measurements showed a progressive increase with higher Cormack-Lehane grades, with the most significant jump between grades 2 and 3.

Discussion

The findings of this prospective cross-sectional study demonstrate a significant and strong correlation between ultrasound-measured tongue dimensions, specifically thickness and volume, and the Cormack-Lehane (CL) grade observed during direct laryngoscopy. Our results confirm the primary hypothesis that quantitative sonographic assessment of the tongue provides a valuable and objective tool for predicting difficult laryngoscopy, outperforming several traditional bedside clinical tests.

The most compelling finding of this study is the excellent discriminatory power of tongue volume (area under the curve [AUC]= 0.912) and tongue thickness (AUC, 0.874) in distinguishing between easy and difficult laryngoscopy. An optimal tongue volume cut-off of >95 cm³ yielded a sensitivity of 87.5% and specificity of 83.3%. This aligns with the anatomical principle underpinning difficult direct laryngoscopy, in which a disproportionately large tongue base occupies space within the oropharyngeal cavity, physically obstructing the line of sight from the mouth to the glottis and making elevation of the epiglottis with a laryngoscope blade more challenging [13]. Our study provides direct, quantitative evidence for this long-held clinical axiom. The strong positive correlation (r = 0.687 for volume and , r = 0.642 for thickness) between these measurements and the CL grade indicates a dose-response relationship, in which increasing tongue size progressively worsens the laryngoscopic view.

These results significantly advance the findings of earlier, foundational studies. For instance, Yadav et al. (2019) demonstrated that tongue thickness, measured in the mid-sagittal plane, had good predictive value for difficult laryngoscopy. [6] Our study builds upon this by incorporating a three-dimensional volumetric assessment, which proved to be an even stronger predictor. This is physiologically intuitive, as laryngoscopic difficulty is likely influenced by the overall bulk of the tongue rather than a single linear dimension. Our volumetric method, using an ellipsoid approximation from measurements in three planes, offers a more comprehensive anatomical assessment.

Furthermore, our findings resonate with but refine those of Adhikari et al. (2011), whose pilot study suggested the utility of point-of-care ultrasound for airway assessment. [9] We have provided specific, validated cut-off values and detailed operating characteristics for tongue parameters, moving from the realm of "potential utility" to quantifiable clinical prediction. The derived cut-off for tongue thickness (>4.3 cm) is also consistent with the ranges suggested in previous literature, lending external validity to our results. [14]

A critical aspect of this discussion is the comparative performance of sonographic tongue assessment against established clinical predictors. In our cohort, the Modified Mallampati Classification (MPC) showed a significant but weaker association with difficult laryngoscopy (AUC = 0.745) than ultrasound parameters. This corroborates the well-documented limitations of the MPC, including its subjective nature, inter-observer variability, and modest accuracy, as highlighted in meta-analyses. [2, 15] The MPC is an indirect surrogate for tongue size, relying on a visual estimation of oropharyngeal structures. In contrast, ultrasound provides a direct, objective, and numerical measurement, likely explaining its superior performance. Our data show that while a high MPC (classes 3 or 4) was associated with difficult laryngoscopy, many patients with a favorable MPC (classes 1 or 2) still experienced difficult laryngoscopy if their tongue volume was elevated. This underscores the potential of ultrasound to identify "false easy" patients missed by conventional screening.

Similarly, thyromental distance (TMD) in our study showed a nonsignificant trend (p=0.064, r=-0.208), whereas sternomental distance was a significant but moderate predictor. The variable performance of these external neck measurements is well known and attributed to their inability to assess internal soft tissue anatomy. [3, 16] They measure skeletal landmarks but do not account for the volume of soft tissue (such as the tongue) that lies in the path of laryngoscopy. Our study reinforces that internal anatomy, accessible via ultrasound, is a more direct determinant of the laryngoscopic view.

The integration of airway ultrasound into routine preoperative evaluation represents a paradigm shift towards objective, image-guided assessment. [4, 17] The pathophysiological rationale is robust: direct laryngoscopy requires displacement of the tongue into the submandibular space. The ease of this maneuver is determined by the compliance and volume of the tongue relative to the capacity of the submandibular compartment. [18] A large, non-compliant tongue resists displacement, resulting in poor glottic visualization . Ultrasound directly quantifies this critical variable.

Our proposed combined model (tongue volume + thickness + MPC) achieved an AUC of 0.943, suggesting that the highest predictive accuracy may come from integrating the objectivity of ultrasound with the rapidity of conventional examinations. A feasible clinical algorithm could involve performing a standard MPC; if it suggests potential difficulty (class 3/4) or if the patient has other risk factors (e.g., obesity, limited neck mobility), rapid tongue ultrasound could be performed for confirmation and quantification. This targeted use would be time-efficient, adding only 2-3 minutes to the pre-anaesthetic check, as demonstrated in our and other studies. [19]

The strong correlation we observed between increased ultrasound parameters and procedural outcomes, such as longer laryngoscopy time, more attempts, and the universal need for airway adjuncts in the difficult group further validates the clinical relevance of these measurements. This transitions the prediction from a theoretical "difficult grade" to tangible operational difficulty, which has direct implications for operating room logistics, preparation of advanced equipment, and alerting senior personnel. [20]

Our work is situated within a growing body of literature exploring various sonographic parameters for airway assessment. Studies have investigated parameters, such as pre-tracheal soft tissue thickness, [21] hyomental distance ratio, [22] and skin-to-epiglottis distance. [10] Each parameter explores a different aspect of airway anatomy. For example, pre-tracheal thickness is particularly relevant in obese patients and may predict difficult ventilation or intubation with videolaryngoscopy. [23] The skin-to-epiglottis distance relates to the depth of the vallecula. Our focus on the tongue complements these approaches. The tongue is the primary anatomical structure manipulated during direct laryngoscopy, making its assessment fundamentally important for this technique.

Kumar et al. (2020), in a study referenced in our protocol, measured the skin-to-mucosa depth at the tongue base and reported a sensitivity of 75%. [24] Our methodology, which measures pure tongue thickness and calculates volume, appears to offer improved sensitivity (87.5%). This may be because our thickness measurement at the base, combined with volumetric calculation, better captures the three-dimensional bulk relevant to displacement. Furthermore, Parab et al. 's(2021) meta-analysis concluded that, in general, airway ultrasound parameters show good diagnostic accuracy;however, the authors highlighted heterogeneity in the parameters used. [12] Our study contributes high-quality data on two specific, anatomically intuitive parameters, thereby aiding in the standardization of this emerging field.

The strengths of this study include its prospective design, blinding of the sonographer and laryngoscopist to minimize bias, use of standardized ultrasound and laryngoscopy protocols, and application of a three-dimensional volumetric calculation. The sample size, although moderate, was adequate according to an a priori calculation and provided statistically robust results.

However, these limitations must be acknowledged. The predictive performance of these cut-offs requires external validation in diverse cohorts. [25] Although we used a standardized formula for volume estimation, this is an approximation. More precise volumetric methods using three-dimensional ultrasound reconstruction exist but are more complex and time-consuming for routine use. [26] Our method represents a pragmatic balance between accuracy and clinical feasibility. Sonographic measurements, although objective, are operator-dependent. However, studies have shown that with basic training, novices can achieve reliable measurements of tongue thickness, supporting its potential for widespread adoption. [5] Our definition of difficult laryngoscopy (CL 2b-4) is widely accepted; however, clinical difficulty is a continuum. We did not assess the correlation with difficult intubation *per se* as a separate outcome, although in our study, all cases of difficult laryngoscopy resulted in difficult intubation.

Future research should focus on multicenter validation of the cut-offs proposed herein. Investigating the role of tongue ultrasound in specific high-risk subgroups, such as obese patients, those with obstructive sleep apnea, or pregnant women, is crucial. [27, 28] The integration of artificial intelligence for automated measurement and interpretation of airway ultrasound images is another promising frontier that could reduce inter-operator variability and simplify the process. [29] Furthermore, research should explore whether pre-operative identification of a large tongue via ultrasound can guide the immediate choice of intubation device, such as opting for a videolaryngoscope first-pass in patients with tongue volume >95 cm^3. This could form the basis for an ultrasound-guided difficult airway algorithm. [30]

From a clinical perspective, the implications are significant. In an era emphasizing patient safety and precision medicine, ultrasound provides a low-cost, non-invasive, and repeatable method to enhance preoperative airway evaluation. [31] It moves beyond the subjective "art" of airway assessment towards a more quantitative "science." For anaesthesiologists, it offers an additional tool to reduce the incidence of unanticipated difficult airways, thereby potentially decreasing associated morbidity. For patients, it represents a step towards more individualized and safer care.

Conclusion

This study provides compelling evidence that ultrasound-measured tongue thickness and, in particular, tongue volume, are strong, independent predictors of Cormack-Lehane grade and difficult direct laryngoscopy. They outperform traditional clinical tests, such as the Mallampati classification, in terms of objective accuracy. The quantification of tongue dimensions offers a direct, reproducible, and anatomically rational method for preoperative airway risk stratification. Although the Mallampati test remains a valuable rapid screening tool, point-of-care ultrasound of the tongue serves as an excellent confirmatory and quantitative test, especially in equivocal or high-risk cases. We advocate for the incorporation of basic tongue ultrasound into the anaesthesiologist's armamentarium for airway assessment as part of a multimodal evaluation strategy to improve patient safety and preparedness in managing potentially difficult airways.

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Author Contributions: