Original Article

A retrospective study of 3D measurement and analysis applied in the morphological evaluation of achalasia cardia

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Background: Achalasia cardia (AC) is defined as a disorder of esophageal motility whose diagnostic gold standard depends on high-resolution manometry (HRM). The invasiveness of HRM can cause difficulties in diagnosis, treatment, and follow-up for patients with AC. Thus, we aimed to investigate the function of 3D reconstruction and measurement to prove the wide application of this alternative non-invasive approach for AC.

Methods: A total of 126 patients with AC and 40 healthy subjects in Tianjin Medical University General Hospital from January 2018 to October 2022 were enrolled in this retrospective study. Chest CT images of these subjects were used to reconstruct the 3D models of the esophagus, stomach, spine, left crus, and right crus. Measurements of esophagus length, volume of esophagus, gastroesophageal insertion angle (His angle), max thickness of esophageal wall, esophagus maximum transverse and longitudinal diameter, esophagus-spine angle, and spine-lower esophageal sphincter (LES) angle were applied based on the models.

Results: Retrocardiac esophagus length, volume of esophagus, max thickness of esophageal wall, esophagus maximum transverse and longitudinal diameter, thoracic esophagus-spine angle, and spine-LES angle in the AC group were higher than those in the control group (all P values <0.05). Among the three subtypes of AC, thoracic esophagus length, intra-abdominal LES length, volume of esophagus, His angle, esophagus maximum transverse and longitudinal diameter, and thoracic esophagus-spine angle all presented statistical differences (all P values <0.05). Correlation analysis revealed that manometric types were positively associated with His angle [r=0.196; 95% confidence interval (CI): 0.009, 0.372; P=0.028] but negatively associated with volume of esophagus (r=−0.480; 95% CI: −0.639, −0.310; P<0.001), esophagus maximum transverse diameter (r=−0.551; 95% CI: −0.679, −0.400; P<0.001), esophagus maximum longitudinal diameter (r=−0.518; 95% CI: −0.649, −0.366; P<0.001), and thoracic esophagus-spine angle (r=−0.324; 95% CI: −0.479, −0.157; P<0.001).

Conclusions: This study successfully presented the differences in esophageal length, volume, thickness, and angles between healthy subjects and different AC subtypes on the basis of 3D reconstruction and measurement. Thus, 3D model and measurement can be regarded as a good support for further research and

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make a valuable contribution to developing non-invasive approaches for AC management.

Keywords: 3D measurement; esophageal model; achalasia cardia (AC); diagnostic method; esophageal disorder

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Introduction

Achalasia cardia (AC) is defined as a rare esophageal smooth muscle disorder characterized by impaired relaxation of the lower esophageal sphincter (LES) and absent or spastic esophageal body contractions (1). Its typical symptoms include dysphagia, regurgitation, chest pain, and weight loss (2). AC can be categorized into three subtypes on the basis of its diagnostic gold standard test, namely, high-resolution manometry (HRM) (2,3). However, given the invasiveness of HRM, a good number of patients cannot tolerate this test, which may lead to missed diagnosis, misdiagnosis, and delayed diagnosis and treatment of AC. In light of this condition, researchers are increasingly inclined to develop new, reliable, and noninvasive means for the diagnosis and treatment of AC. Some studies have been conducted in 2D planes. Licurse *et al.* proved the effectiveness of chest computed tomography (CT) in terms of differentiating primary and secondary AC (4). Ishii *et al.* found that performing chest CT scan in a timely fashion can avoid the delayed diagnosis of AC (5). CT esophagram was also found to be useful for the evaluation of post-peroral endoscopic myotomy (POEM) management (6). Through 2D measurement, researchers can observe esophageal thickness and esophageal length, but they cannot measure the angle relationship between the esophagus and its adjacent anatomical structure, which may be closely associated with clinical symptoms and prognosis of AC and can be measured accurately by 3D reconstruction.

The 3D reconstruction technique based on CT imaging has been increasingly used in some areas of diseases, such as female pelvic tumors, prostatic hyperplasia, and infertility, especially as an auxiliary method for some surgical operations (7-11). A prospective study investigated differences in the 3D pressure profile of LES and hiatal contraction between normal subjects and patients with AC, their results indicated the anatomical and functional abnormalities of the crural diaphragm muscle in patients with AC, suggesting that creative 3D reconstruction can be regarded as a promising direction for AC management (12).

Collectively, the objectives of our study were as follows. First, we aimed to carry out 3D reconstruction based on CT imaging to observe anatomical features of healthy subjects and patients with AC. Second, we planned to perform 3D measurement according to the reconstructed anatomical structure including esophagus zone, stomach zone, spine, left crus, and right crus. Finally, we would compare the differences in parameters on the basis of various grouping methods. This work was designed to contribute to the wide application of 3D measurement and further development of an alternative non-invasive diagnostic approach for AC. We present this article in accordance with the STROBE reporting checklist (available at https://qims.amegroups.com/article/view/10.21037/qims-23-626/rc).

Methods

Study population and data collection

This cross-sectional retrospective study was conducted between January 2018 and October 2022. It included 160 patients diagnosed with AC by HRM from Tianjin Medical University General Hospital. The exclusion criteria were as follows: patients combined with other esophageal-related diseases, patients combined with other chronic diseases or malignant tumors, or patients without complete CT image data. All of the clinical and imaging materials were collected and assessed by two researchers. Through this process, 126 patients were included for final analysis (*Figure 1*). The clinical information and CT image data from 40 healthy test subjects were also collected in this research as controls. These healthy individuals were shown to be free from any esophageal motility disorders, chronic diseases, or malignant tumors. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Ethics Committee of Tianjin Medical University General Hospital (No. IRB2023-WZ-054) and individual consent for this retrospective analysis was waived.

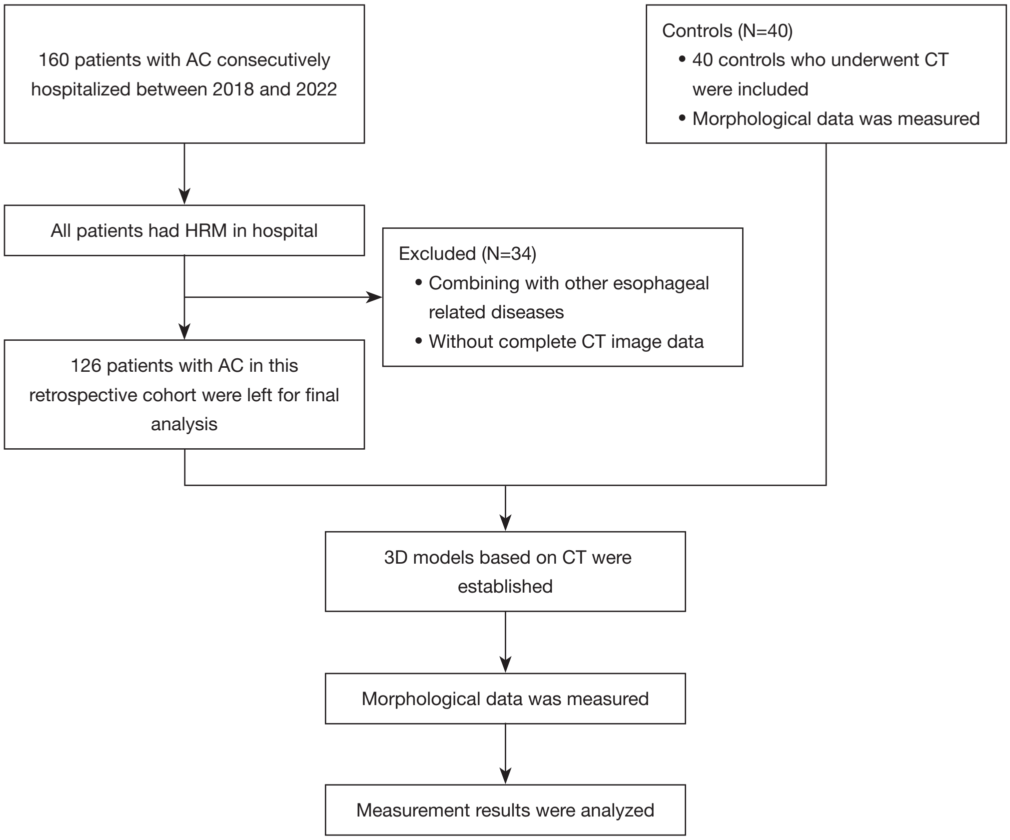

Figure 1 Flow diagram for study. AC, achalasia cardia; HRM, high-resolution manometry; CT, computed tomography.

3D reconstruction

The axial 2D CT images in DICOM format with a slice thickness of 5 mm were imported into Mimics software 19.0 (Materialize, Leuven, Belgium). Subsequently, we reconstructed the model of the esophagus zone, stomach zone, spine, left crus, and right crus and used Geomagic Studio 14.0 (Geomagic, Rock Hill, SC, USA) for further smoothing. Finally, we used 3-matic software 11.0 (Materialize, Leuven, Belgium) to carry out measurements and analyses on the basis of the reconstructed 3D models. All 3D reconstructions, measurements, and analyses were completed and checked by three researchers.

Parameter measurements and analysis

Through 3-matic software, we measured the thoracic esophagus length, retrocardiac esophagus length, and intra-abdominal LES length by generating the esophagus centerline. Esophagus maximum transverse diameter and maximum longitudinal diameter were defined as the length of the line from the leftmost point to the rightmost point and the length of the line from the frontmost point to the lastmost point in 3D models, respectively. The volume of the esophagus can be viewed and calculated by "Mimics software → properties". We also measured the max thickness of the esophageal wall.

Standard sagittal and coronal planes were made through the center of the tenth thoracic cone. In the sagittal plane, the thoracic esophagus-spine angle was defined as the angle between the sagittal plane and thoracic esophagus centerline, whereas the retrocardiac esophagus-spine angle was defined as the angle between the sagittal plane and retrocardiac esophagus centerline. The spine-LES angle was defined as the angle between the intra-abdominal LES and the plane (sagittal and coronal). We also defined right deflection angle as the positive angle and left deflection angle as the negative angle.

The gastroesophageal insertion angle (His angle) was defined as the smallest angle, which was formed by the intra-abdominal LES centerline and gastroesophageal line.

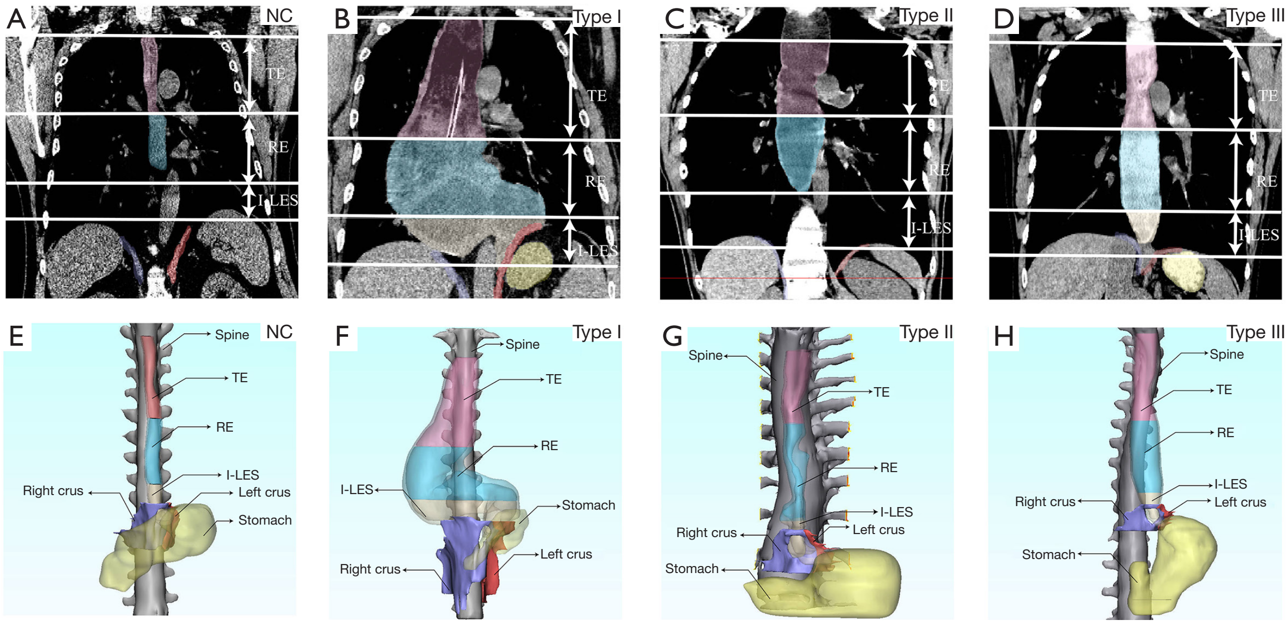

Figure 2 Comparison of 3D models between a NC and AC patients. (A) The 2D scanning image of a NC. (B-D) The 2D scanning image of different subtypes of AC patients. (E) 3D model of a NC. (F-H) 3D models of different subtypes of AC patients. NC, normal control; TE, thoracic esophagus; RE, retrocardiac esophagus; I-LES, intra-abdominal lower esophageal sphincter.

Statistical analysis

Characteristics of participants were described. Normally distributed continuous variables were presented as mean and standard deviation (SD), whereas non-normally distributed continuous variables were presented as median and interquartile range (IQR). Categorical variables were presented as number and percentage. Two independent-sample *t*-tests or Mann-Whitney *U* test was used to compare the measurement parameters of different groups. The Shapiro-Wilk test was used to conduct the normality test with sample size less than 50. The Kolmogorov-Smirnov test was used to conduct the normality test with sample size more than 50. Comparisons between different groups were made by one-way analysis of variance (ANOVA) or Kruskal-Wallis test. A two-tailed P value <0.05 was considered statistically significant. All statistical analyses were performed using SPSS version 24 (IBM, Armonk, NY, USA).

Results

Among 126 patients with AC, 45 patients were classified as type I, 66 were classified as type II, and 15 were classified as type III. Our cohort contained 56 men and 70 women, with a median age of 51 [36–62.50], 47 [34–61], and 48 [31–63] years. *Figure 2* shows the 3D models of the esophagus zone, stomach zone, spine, left crus, and right crus and compared measurements between healthy subjects and different AC subtypes. In *Figures 3-5*, we depicted one typical model of a patient with AC to demonstrate some essential parameters visually and quantitatively, including esophagus length, esophagus maximum transverse and longitudinal diameter, volume of esophagus, esophageal thickness, His angle, and spine-LES angle.

Table 1 presents a comparison between healthy controls and patients with AC. Retrocardiac esophagus length, volume of esophagus, max thickness of esophageal wall, esophagus maximum transverse diameter, esophagus maximum longitudinal diameter, thoracic esophagus-spine angle, and spine-LES angle all presented statistical differences.

Table 2 shows the characteristics of patients according to manometric types. HRM parameters, thoracic esophagus length, intra-abdominal LES length, volume of esophagus, His angle, esophagus maximum transverse diameter, esophagus maximum longitudinal diameter, and thoracic esophagus-spine angle all presented statistical differences. *Figure 6* shows that manometric types were positively

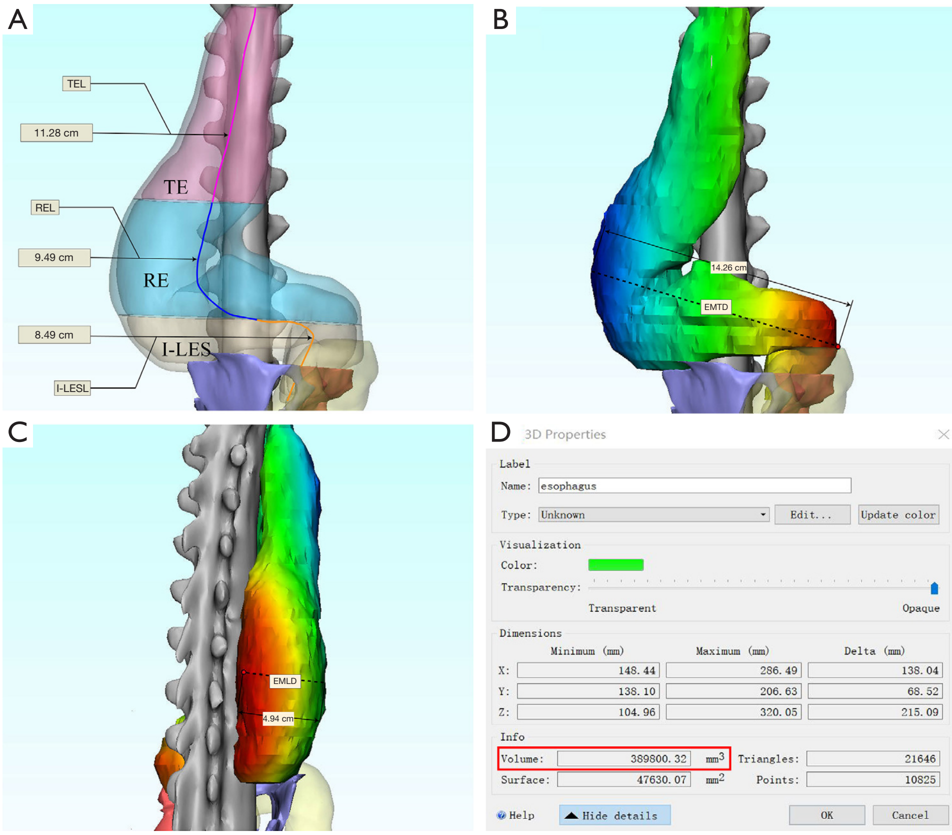

Figure 3 3D models of esophageal length, transverse diameter, longitudinal diameter, and volume of esophagus of an AC patient. (A) The TEL was 11.28 cm, the REL was 9.49 cm, the I-LESL was 8.49 cm. (B) The EMTD was 14.26 cm. (C) The EMLD was 4.94 cm. (D) The VE was 389,800.32 mm^3. TEL, thoracic esophagus length; TE, thoracic esophagus; REL, retrocardiac esophagus length; RE, retrocardiac esophagus; I-LESL, intra-abdominal lower esophageal sphincter length; I-LES, intra-abdominal lower esophageal sphincter; EMTD, esophagus maximum transverse diameter; EMLD, esophagus maximum longitudinal diameter; VE, volume of esophagus.

associated with His angle [r=0.196; 95% confidence interval (CI): 0.009, 0.372; P=0.028] but negatively associated with volume of esophagus (r=−0.480; 95% CI: −0.639, −0.310; P<0.001), esophagus maximum transverse diameter (r=−0.551; 95% CI: −0.679, −0.400; P<0.001), esophagus maximum longitudinal diameter (r=−0.518; 95% CI: −0.649, −0.366; P<0.001), and thoracic esophagus-spine angle (r=−0.324; 95% CI: −0.479, −0.157; P<0.001).

Discussion

In this retrospective study, we conducted 3D reconstruction and measurements based on CT imaging and identified some essential parameters, which can be used to differentiate healthy controls and three subtypes of AC. The results of our study demonstrated the feasibility of 3D reconstruction and measurement for the management of AC. First, we found that some parameters present statistical differences between patients with AC and healthy controls, including retrocardiac esophagus length, volume of esophagus, max thickness of esophageal wall, esophagus maximum transverse diameter, esophagus maximum longitudinal diameter, thoracic esophagus-spine angle, and spine-LES angle (*Table 1*). Although HRM is a golden standard for AC diagnosis, its invasiveness makes it unacceptable and unfriendly to some patients in clinical practice. Moreover, some patients suffering severe dysphagia have difficulties in receiving the contrast medium for the examination of esophagography. Considering the above facts, we believe that 3D reconstruction can be used as a more convenient screening tool for the assessment of esophageal structure and function by measuring the parameters acquired from

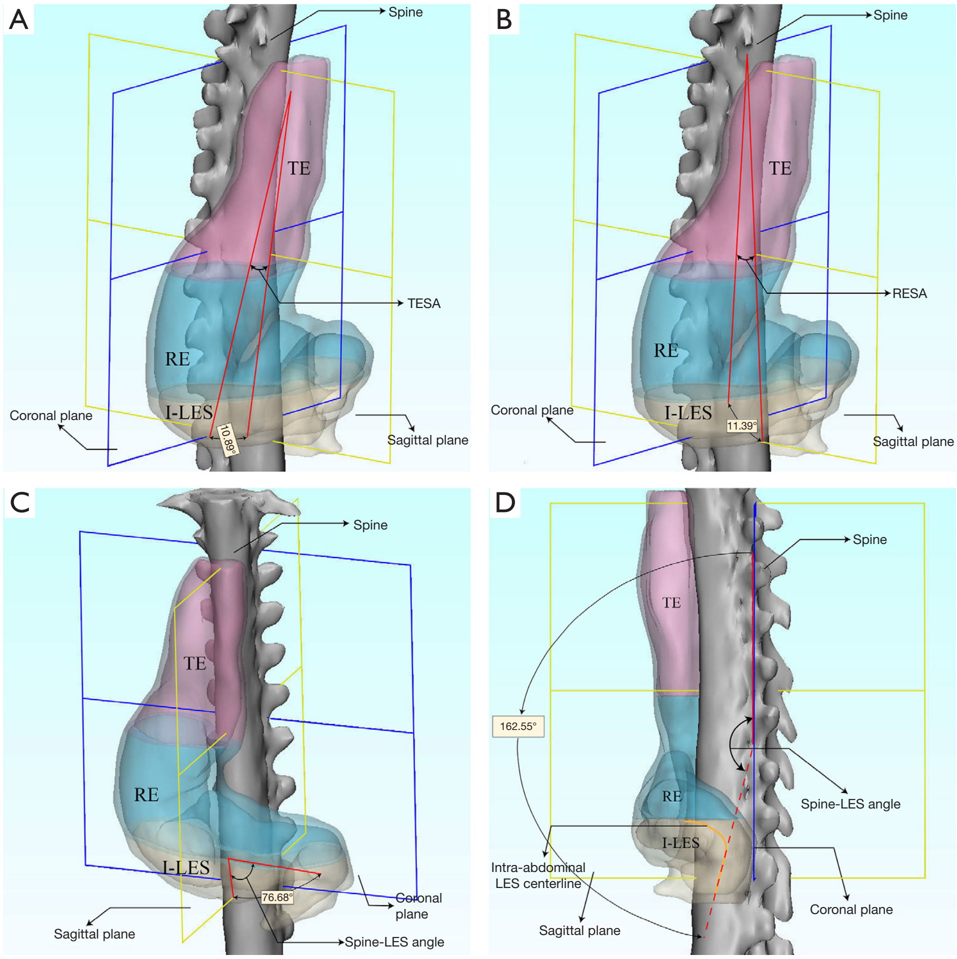

Figure 4 3D models of esophagus-spine angle and spine-LES angle of an AC patient. (A-D) TESA was 10.89°, RESA was 11.39°, the spine-LES angle in sagittal plane was 76.68°, and the spine-LES angle in coronal plane was 162.55°. TE, thoracic esophagus; TESA, thoracic esophagus-spine angle; RE, retrocardiac esophagus; I-LES, intra-abdominal lower esophageal sphincter; RESA, retrocardiac esophagus-spine angle; LES, lower esophageal sphincter.

the safe and harmless CT scan. Second, some parameters can also be used to differentiate three subtypes of AC statistically, such as esophageal length, volume of esophagus, His angle, esophagus maximum transverse and longitudinal diameter, and thoracic esophagus-spine angle (*Table 2*). Further, manometric types were correlated with His angle, esophageal volume, thoracic esophagus-spine angle, esophagus maximum transverse diameter, and esophagus maximum longitudinal diameter (*Figure 6*). These all indicated that 3D parameters could be potentially regarded as AC-specific parameters. For patients who are unwilling and unable to receive HRM, 3D reconstruction could be an effective and safe alternative to evaluate their condition preliminarily.

In detail, the parameters of our 3D models could be divided into three groups. One group was used to assess the dilation grading and morphological change of the esophagus and the corresponding parameters including esophageal thickness and volume of esophagus. Our results showed that the above parameters of patients with AC were higher than those of healthy subjects, which were consistent with the fact that patients with AC were more likely to have esophageal dilation than healthy subjects. Among three subtypes, type I AC patients tended to have larger volume of esophagus and esophageal thickness, which was in line with the study that this type of patients tended to have severer dilation (13). The other group was used to evaluate the symptoms of AC. We selected esophageal length and His

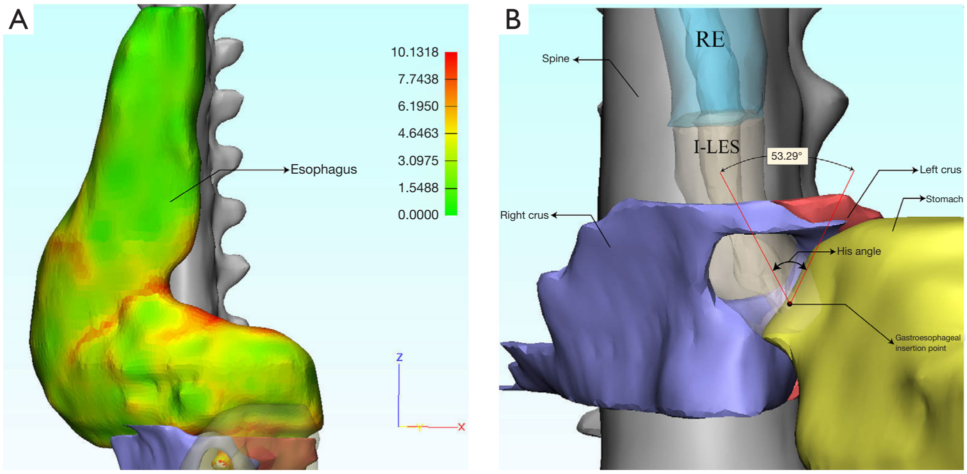

Figure 5 3D models of thickness of esophageal wall and His angle of an AC patient. (A) The thickness distribution nephogram illustrated that the red part represents the high thickness distribution, and the green part represents the low thickness distribution. The max thickness of EW was 10.1318 mm. (B) The His angle was 53.29°. RE, retrocardiac esophagus; I-LES, intra-abdominal lower esophageal sphincter; His angle, gastroesophageal insertion angle; EW, esophageal wall.

Table 1 Comparison of healthy control and AC patients

Parameters	Control (n=40)	AC (n=126)	P
Age (years)	52.50 (46.25, 57.75)	48 (34, 61.25)	0.694
Sex			0.643
Male	20 (50.00)	56 (44.40)	
Female	20 (50.00)	70 (55.60)	
Measurement indicators			
TEL (cm)	8.84 (8.39, 9.75)	9.23 (8.15, 10.70)	0.342
REL (cm)	8.64 (8.13, 9.52)	9.84 (8.63, 11.07)	0.006*
I-LESL (cm)	4.63 (3.38, 5.35)	4.31 (3.27, 5.61)	0.785
VE (mm^3)	30,156.50 (26,987.50, 33,765)	137,021 (61,866.78, 234,463.33)	<0.001*
His angle (°)	81.84 (74.57, 97.28)	88.26 (74.53, 102.46)	0.183
Max thickness of EW (mm)	4.10 (3.55, 4.60)	7.18 (6.06, 8.97)	<0.001*
EMTD (cm)	1.91 (1.60, 2.21)	3.83 (2.65, 5.19)	<0.001
EMLD (cm)	2.02 (1.71, 2.29)	2.72 (1.89, 3.55)	0.006*
TESA (°)	–5.18 (–7.43, –3.10)	8.55 (2.80, 14.18)	<0.001*
RESA (°)	4.33 (–2.55, 5.99)	3.86 (–7.46, 13.06)	0.509
Spine-LES angle in sagittal plane (°)	–19.09 (–23.94, –12.84)	–24.96 (–34.19, –14.30)	0.028*
Spine-LES angle in coronal plane (°)	164.42 (157.88, 168.99)	170.70 (161.33, 175.15)	0.045*

Data are presented as median (IQR) or n (%). *, P<0.05. AC, achalasia cardia; TEL, thoracic esophagus length; REL, retrocardiac esophagus length; I-LESL, intra-abdominal lower esophageal sphincter length; VE, volume of esophagus; His angle, gastroesophageal insertion angle; EW, esophageal wall; EMTD, esophagus maximum transverse diameter; EMLD, esophagus maximum longitudinal diameter; TESA, thoracic esophagus-spine angle; RESA, retrocardiac esophagus-spine angle; LES, lower esophageal sphincter; IQR, interquartile range.

Table 2 Comparison of 3D model parameters in different manometric types

Parameters	Type I (n=45)	Type II (n=66)	Type III (n=15)	P
Age (years)	51 [36, 62.50]	47 [34, 61]	48 [31, 63]	0.735
Sex				0.225
Male	22 (48.90)	25 (37.90)	9 (60.00)	
Female	23 (51.10)	41 (62.10)	6 (40.00)	
Measurement indicators				
DCI (mmHg·s·cm)	12.90 [6.30, 38.80]	75.79 [49.18, 90.98]	1,136.20 [862, 2,005]	<0.001*
LES IRP 4 s (mmHg)	20.20 [16.55, 24.40]	34.40 [25.03, 47.20]	28.70 [23.50, 35.70]	<0.001*
DL (s)	10.80 [8.10, 14.12]	7.95 [6.22, 11.25]	4.42 [3.57, 5.52]	0.001*
TEL (cm)	10.35 [8.76, 10.99]	8.73 [7.59, 10.02]	9.60 [8.78, 11.25]	0.005*
REL (cm)	10.06±2.35	9.88±1.94	9.53±1.57	0.681
I-LESL (cm)	4.77 [3.67, 6.13]	3.85 [2.73, 5.16]	4.95 [3.63, 5.91]	0.004*
VE (mm^3)	233,015 [181,310.50, 357,935]	83,834.22 [43,201.69, 158,681.92]	118,320 [23,805, 281,898]	<0.001*
His angle (°)	76.47±25.19	96.78±15.76	78.09±20.22	<0.001*
Max thickness of EW (mm)	8.13 [6.23, 9.98]	6.76 [5.81, 7.96]	7.38 [6.63, 8.46]	0.075
EMTD (cm)	5.32 [4.06, 6.31]	3.09 [1.99, 4]	3.49 [1.55, 4.62]	<0.001*
EMLD (cm)	3.71 [2.79, 5.10]	2.16 [1.60, 2.91]	2.70 [1.30, 3.24]	<0.001*
TESA (°)	12.94 [6.36, 16.21]	7.77 [2.02, 12.31]	2.27 [0.52, 8.83]	0.001*
RESA (°)	2.69 [−10.71, 12.13]	5.30 [−5.31, 14.68]	2.85 [−11.54, 11.07]	0.188
Spine-LES angle in sagittal plane (°)	−22.69 [−41.57, −10.95]	−26.76 [−33.44, −15.75]	−25.15 [−27.29, −19.41]	0.543
Spine-LES angle in coronal plane (°)	170.42 [158.78, 175.23]	170.74 [161.78, 175.83]	169.54 [163.94, 173.84]	0.916

Data are presented as median [IQR], n (%), or mean ± SD. *, P<0.05. DCI, distal contractile integral; LES IRP 4 s, the 4 s integrated relaxation pressure of lower esophageal sphincter; DL, distal latency; TEL, thoracic esophagus length; REL, retrocardiac esophagus length; I-LESL, intra-abdominal lower esophageal sphincter length; VE, volume of esophagus; His angle, gastroesophageal insertion angle; EW, esophageal wall; EMTD, esophagus maximum transverse diameter; EMLD, esophagus maximum longitudinal diameter; TESA, thoracic esophagus-spine angle; RESA, retrocardiac esophagus-spine angle; LES, lower esophageal sphincter; IQR, interquartile range; SD, standard deviation.

angle to assess the degree of reflux, which have been studied in gastroesophageal reflux disease (GERD) (14,15). Studies have reported that patients with shorter intra-abdominal LES length and larger His angle have severer reflux than their counterparts in GERD (16,17). In our research, patients with type II AC also had shorter intra-abdominal LES length and larger His angle, indicating that this type of patients appeared to have severer reflux symptom than the two other subtypes. The luminal change has shown to be related to the severity of AC in 2D plane, so we similarly measured esophagus maximum transverse and longitudinal diameter in 3D plane (18). In our study, patients with type I AC tended to have larger esophagus maximum transverse diameter and longitudinal diameter. This can be explained by the fact that type I AC was more intended to develop to the end-stage of AC and thus had the severer condition (1). Another group was used to assess the esophageal tortuosity and corresponding parameters including esophagus-spine angle and spine-LES angle. We found no relevant studies on esophageal tortuosity in 3D models. Previous studies mostly centered on the changes in esophageal tortuosity in the 2D plane and have found that POEM can ameliorate reflux symptoms by increasing the angle of esophageal tortuosity (19,20). Thus, we believe it is meaningful to measure

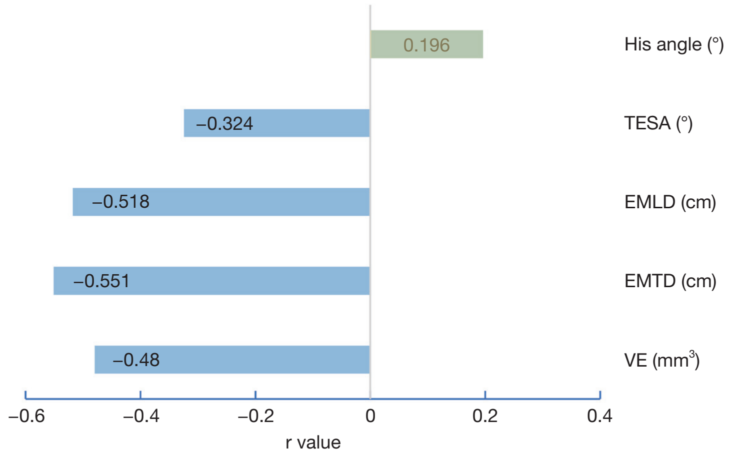

Figure 6 Correlation analysis between manometric types and parameters of 3D models. His angle, gastroesophageal insertion angle; TESA, thoracic esophagus-spine angle; EMLD, esophagus maximum longitudinal diameter; EMTD, esophagus maximum transverse diameter; VE, volume of esophagus.

esophagus-spine angle in 3D plane. But in our research, we cannot reach a solid conclusion that esophagus-spine angle was associated with the reflux symptom. The spine-LES angle was used to assess the pressure of LES (12). Our results showed that the spine-LES angle in AC group was larger than that of healthy control, which was contrary to previous study. We believe these issues can be addressed by expanding sample size and certainly worthy of investigating further. Through 3D reconstruction, we assessed the dilation grading and esophageal morphology and measured some essential parameters, to evaluate the anatomic abnormality of the esophagus, which may be associated with clinical symptoms and predict prognosis. We believe this advantage can become a promising direction in AC and even other esophageal motility disorders, as well as benefit patients.

This study had some limitations. First, although we reconstructed the 3D model of the esophagus, stomach, spine, and crus and provided a new method for the management of AC, this method must still be performed manually, so it is time-consuming and causes selection bias. We should develop an automatic means to complete these complicated procedures in the future. Second, we only included 40 healthy subjects, which may cause data bias. Third, although AC is a rare digestive disease, our sample size must be expanded for further study. Finally, our study was only a retrospective study on healthy controls and patients with AC, without the analysis and comparison of other esophageal motility diseases. This step will be performed in our further research. Taken together, this creative method can be potentially regarded as a noninvasive and precise alternative for the management of AC.

Conclusions

This study successfully presented the differences in 3D parameters between healthy subjects and different AC subtypes. The 3D reconstruction and measurement could be regarded as a good support for developing non-invasive tools for AC management.

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Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://qims.amegroups.com/article/view/10.21037/qims-23-626/rc

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://qims.amegroups.com/article/view/10.21037/qims-23-626/coif).

The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Ethics Committee of Tianjin Medical University General Hospital (No. IRB2023-WZ-054) and individual consent for this retrospective analysis was waived.

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