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ORIGINAL ARTICLE
Craniofacial

Computed Tomography–based Measurement of Herniated Orbital Volume Following Acute Orbital Fractures

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Background: To predict which patients will develop more than 2 mm of enophthalmos and require surgery after orbital fracture is challenging. Although high herniated orbital volume (HV) might be a predictor, its measurement can be complex and time-consuming. This study aimed to identify a simple, reliable, and clinically applicable method for measuring herniated orbital volume.

Methods: This single-center retrospective study examined HV and approximate volume in 42 patients with an orbital floor fracture (OF group) and 56 patients with a medial wall fracture (MW group). Approximate herniated volume (AV) was calculated as a rectangular parallelepiped, quadrangular pyramid, or hemiellipsoid. The correlation between HV and AV was analyzed quantitatively. Receiver operating characteristic curve analysis was performed to compare AV and HV cutoff values.

Results: AV calculated as a hemiellipsoid (AVhe) provided the closest approximation to HV. Correlation analysis showed a positive linear relationship between HV and AVhe in both the OF group ($r = 0.818$) and the MW group ($r = 0.84$). The optimal AVhe cutoff value was 1.013 mL in the OF group (positive and negative predictive values, 96.3% and 66.7%, respectively; area under the curve, 0.925) and 1.13 mL in the MW group (positive and negative predictive values, 90.0% and 69.2%, respectively; area under the curve, 0.956). High HV was defined as greater than 1.0 mL in the OF group and greater than 0.9 mL in the MW group.

Conclusions: A simplified method that approximately calculates the volume of herniated orbital contents in a hemiellipsoid pattern model proved to be practical, easy, and reliable. *(Plast Reconstr Surg Glob Open 2025;13:e6689; doi: 10.1097/GOX.0000000000006689; Published online 16 April 2025.)*

INTRODUCTION

Early repair of orbital fractures and repositioning of any herniated orbital contents are crucial to prevent impairment of the field of vision and eye movement.[1] Delayed repair can be technically challenging owing to the development of fibrosis and may increase the risk of unsatisfactory results.[2]

Persistent diplopia, posttraumatic enophthalmos (PE), and orbital content entrapment are established indications for surgical repair.[3–6] More than 2 mm of PE can cause cosmetic and functional morbidity and is generally considered clinically significant.[4,7–15] However, posttraumatic orbital edema and periocular swelling may cause the development of PE to be delayed until the ideal period for surgical intervention has passed.[16,17] Therefore, surgical decision-making regarding orbital fractures early after the injury can be difficult.

Estimating which patients will develop more than 2 mm of PE and require surgery can optimize treatment outcomes by minimizing the risks associated with unnecessary or delayed intervention.[18] Previous studies have attempted to clarify the correlation between the degree of PE and several anatomic parameters present on computed tomography (CT) at the time of injury. In a systematic review, 5 factors influenced the development of delayed PE: orbital defect height and width, involvement of specific intraorbital structures, rounding of the inferior rectus muscle, orbital fracture area, and volumetric analysis stratified by fracture site.[19] Several studies have

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incorporated these parameters into predictive algorithms used as clinical tools.[18,20,21] Herniated orbital volume (HV) is frequently incorporated into these algorithms. However, HV measurement can be complex and time-consuming, as it requires meticulous manual tracing of intricate borders. Moreover, the thinner the CT slice, the more layers need to be traced.[20]

This study aimed to identify a simple yet reliable method for measuring HV. We hypothesized that an approximate volume, calculated by measuring only 3 dimensions on CT, could replace the conventional method of tracing borders in great detail. The shapes of the approximate volumes were compared and analyzed as rectangular parallelepiped, quadrangular pyramid, or hemiellipsoid.

Takeaways

Question: The purpose of this study is to identify a simple, reliable, and clinically applicable method for measuring herniated orbital volume in patients with orbital fractures.

Findings: This study analyzed clinical data, including herniated orbital volume and approximate herniated volume, as determined by computed tomography, in 42 patients with orbital floor fractures and 56 patients with medial wall fractures. Approximate herniated volume calculated as a hemiellipsoid provided the closest approximation to herniated orbital volume.

Meaning: The simplified method using approximate volume calculated as a hemiellipsoid proved to be more practical, easier, and more reliable than conventional methods.

MATERIALS AND METHODS

Patients

All patients with orbital fractures who were treated by the plastic and reconstructive surgery department in our institution between January 2008 and June 2021 were retrospectively reviewed. Patients who did not undergo initial facial bone CT within 1 week of injury and those with bilateral orbital fractures, lateral orbital wall fractures, orbital roof fractures, inferomedial orbital fractures, fractures of the inferomedial buttress, and linear orbital fractures were excluded. We also excluded patients with concomitant midfacial fractures other than nasal bone fractures. None of the study patients had a history of orbital injury, orbital surgery, or congenital craniofacial anomaly.

The study was approved by the institutional review board of our medical center (No. 2023-047). The requirement for written informed consent was waived owing to its retrospective nature.

Data Collection

Patient data, including age, sex, cause of injury, laterality of injury, fracture location, and the interval between injury and initial facial bone CT were collected from the electronic medical record (Fujifilm Medical Co., Ltd., Tokyo, Japan).

CT Findings

Facial bone CT (slice thickness ≤3 mm) was reviewed using standard bone and soft-tissue windows to assess HV and other parameters. All parameters were measured 3 times by a single plastic surgeon using Synapse software (Fujifilm Medical Co., Ltd.); parameter mean values were calculated for analysis. Patients were grouped according to fracture location: orbital floor (OF) and medial wall (MW).

In the OF group, the maximum length of the fracture line on coronal and sagittal CT views was denoted as X and Y, respectively; in the MW group, the maximum length on coronal and axial CT views was denoted as X and Y, respectively. In both groups, the maximum distance that the fractured part was displaced was measured on a coronal view and designated as Z (Figs. 1, 2). Herniated orbital tissue was defined as soft tissue that extended beyond the normal orbital boundaries into the maxillary or ethmoid sinuses and was manually outlined on coronal views. The cross-sectional areas of the herniated tissue on each coronal slice were summed and multiplied by the slice thickness to determine HV. The approximate herniated volume (AV) was calculated using 3 different shape assumptions: rectangular parallelepiped (AVrp) was calculated as XYZ, quadrangular pyramid (AVqp) as $XYZ/3$, and hemiellipsoid (AVhe) as $\pi XYZ/6$ (Figs. 1, 2).

Statistical Methods

Statistical analyses were conducted using EZR on R Commander version 1.52 (Jichi Medical University, Saitama, Japan).[22] Categorical variables are expressed as numbers with percentages and were compared using the Fisher exact test. Continuous variables are presented as means with SD. Two-group comparisons of continuous data were performed using the Student t test. Three-group comparisons were performed using analysis of variance; if a significant P value was found, the Student t test was then used to identify which specific group pairings exhibited a significant difference. Correlation was assessed using the Pearson method.

Receiver operating characteristic (ROC) curve analysis was performed to compare the AV and HV cutoff values, as high HV had been associated with PE of 2 mm or more. Based on previous studies,[13,23,24] high HV was defined as greater than 1.0 mL in the OF group and greater than 0.9 mL in the MW group. The area under the ROC curve (AUC) was calculated as a measure of predictive performance, which was categorized as follows: AUC 0.5–0.6, failure; AUC 0.6–0.7, poor; AUC 0.7–0.8, fair; AUC 0.8–0.9, good, and AUC 0.9–1.0, excellent. The optimal cutoff value was selected to maximize the sum of sensitivity and specificity. A P value less than 0.05 was considered significant.

RESULTS

Of the 330 patients with orbital fractures identified during the study period, 89 were excluded because of

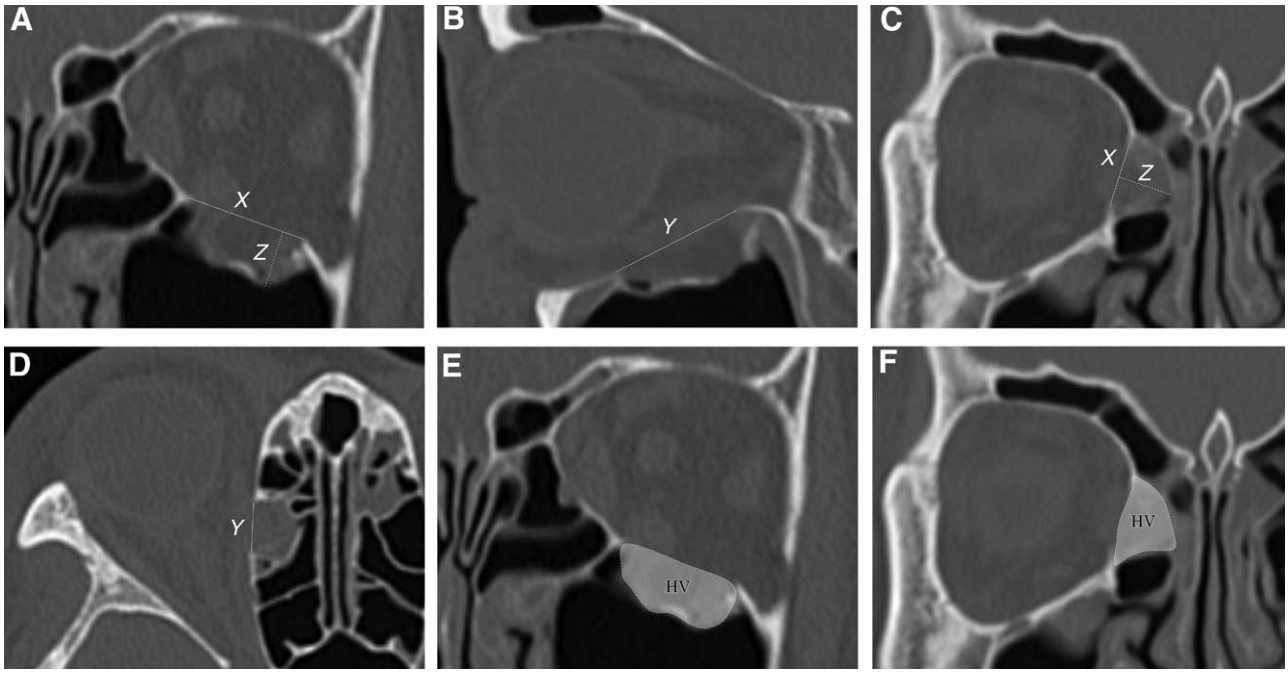

Fig. 1. Measurement of CT parameters and HV. A and B, OF fracture. Coronal and sagittal sections were used to define *X* and *Y* as the maximum length of the bone defect. On the coronal section, Z was established as the maximum distance the fractured portion moved. C and D, MW orbital fracture. Coronal and axial sections were used to determine *X* and *Y*, and *Z* was determined on the coronal section. E and F, The herniated volume was traced on each coronal slice (dashed line and labeled "HV").

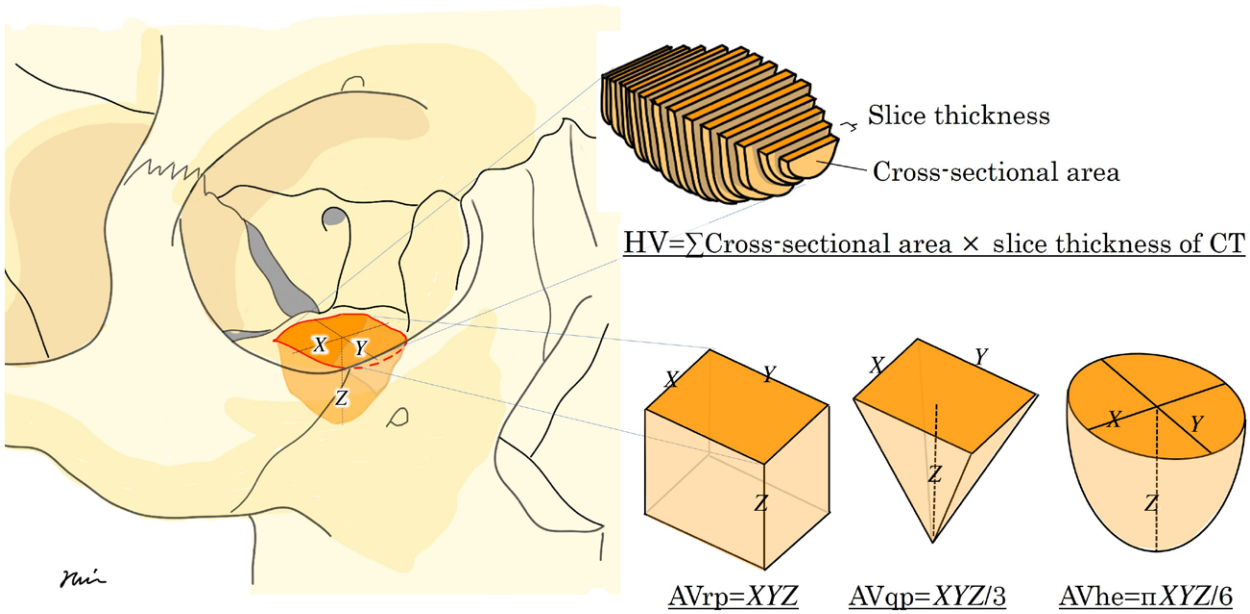

Fig. 2. HV and AV. *XYZ* in the schema corresponds to *XYZ* in the CT parameters.

other facial bone trauma. Among the remaining 241, the most frequent fracture location was the OF (n = 129; 53.5%), followed by the MW (n = 76; 31.5%). The primary mechanisms of injury included sports-related incidents (n = 49; 20.3%), falls (n = 35; 14.5%), and traffic accidents (n = 24; 10.0%).

A total of 143 patients were excluded because their initial CT images were not available (n = 96) or they had sustained bilateral orbital fractures, orbital roof fractures, inferomedial orbital fractures, or linear orbital fractures (n = 47). Finally, 98 patients were included for analysis. Mean age was 42.3 ± 22.5 years (range, 13–89 y).

The cohort comprised 68 men (69.4%) and 30 women (30.6%). The laterality of fracture was right in 50 patients (51.0%). Sixteen patients underwent operative management (16.3%). The OF group consisted of 42 (42.9%) patients and the MW group comprised 56 (57.1%). Patient characteristics are summarized in Table 1. In the OF group, the mean HV was 2.03 ± 1.38 mL, the mean AVrp was 2.9 ± 1.90 mL, the mean AVqp was 0.97 ± 0.63 mL, and the mean AVhe was 1.52 ± 1.00 mL. The corresponding mean volumes in the MW group were 1.40 ± 1.38, 2.29 ± 1.78, 0.76 ± 0.59, and 1.48 ± 1.33 mL, respectively.

To determine which approximate volume shape best approximates the actual hernia volume, we calculated the difference between HV and AVrp/AVqp/AVhe. In the OF group, the mean HV–AVrp difference was 1.11 ± 0.88 mL, the mean HV–AVqp difference was 1.07 ± 0.94 mL, and the mean HV–AVhe difference was 0.62 ± 0.73 mL; the differences in mean values were significant in the analysis of variance ($P = 0.016$). The corresponding mean differences in the MW group were 0.97 ± 0.89, 0.65 ± 0.93, and 0.54 ± 0.83 mL, respectively; these mean differences were also significantly different ($P = 0.032$).

The direct comparisons of mean differences in the OF and MW groups are shown in Figure 3. In the OF group, the mean HV–AVhe difference significantly differed from both the mean HV–AVhrp difference ($P = 0.006$) and the mean HV–AVqp difference ($P = 0.018$); the difference between the mean HV–AVrp difference and the mean HV–AVqp difference was not significant ($P = 0.81$). In the MW group, only the difference between the HV–AVrp mean difference and the HV–AVhe mean difference was significant ($P = 0.01$).

Scatterplots with the Pearson correlation analysis of HV and AVhe in the OF and MW groups are shown in Figure 4. Correlation analysis showed a positive linear relationship between HV and AVhe in both the OF group ($r = 0.818$; $P < 0.001$) and the MW group ($r = 0.846$; $P < 0.001$).

Tables 2 and 3 show the comparison of the high and low HV subgroups in both the OF group (Table 2) and the MW group (Table 3). Age, sex, and fracture laterality did not significantly differ between the high and low HV subgroups in the OF group. In the MW group, age and sex did not significantly differ between the subgroups but fracture site laterality did ($P = 0.011$). These findings suggest that the high and low HV subgroups in each group were fairly similar.

ROC curves for the association of AVhe with high HV in the OF group (HV > 1.0 mL) and MW group (HV > 0.9 mL) are shown in Figure 5. The optimal AVhe cutoff value in the OF group was 1.013 mL (sensitivity of 83.9%, specificity of 90.9%, positive predictive value of 96.3%, negative predictive value of 66.7%, and AUC of 0.925 [95% confidence interval, 0.848–1]). In the MW group, the optimal AVhe cutoff value for predicting high HV was 1.13 mL (sensitivity of 77.1%, specificity of 100%, positive predictive value of 90.0%, negative predictive value of

Table 1. Patient Characteristics

Characteristics of Analysis Population	
Sample size	98
OF, n (%)	42 (42.9)
MW, n (%)	56 (57.1)
Age, mean ± SD, y	42.3 ± 22.5
Sex, n (%)	
Men	68 (69.4)
Women	30 (30.6)
Fractures site, n (%)	
Right	50 (51.0)
Left	48 (49.0)
Treatment, n (%)	
Surgical repair	16 (16.3)
Conservative	82 (83.7)

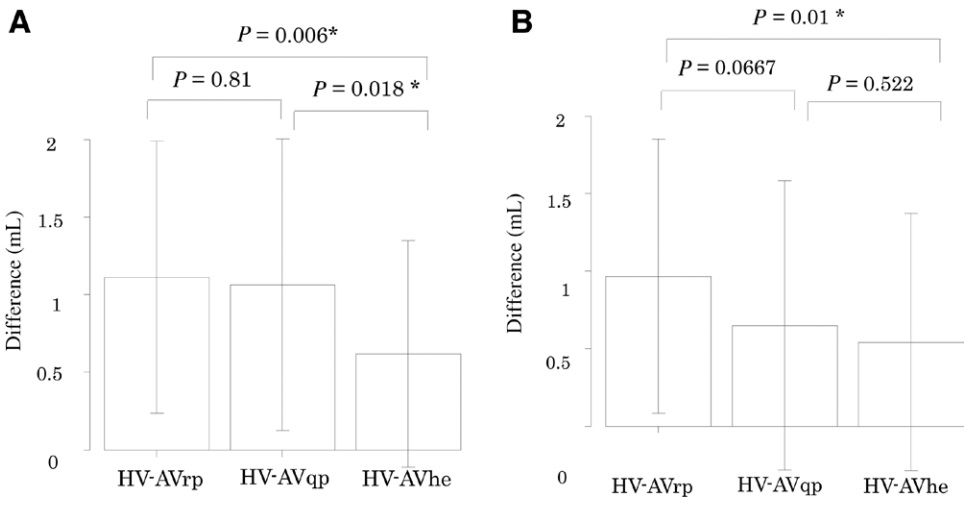

Fig. 3. Comparison of the differences between herniated orbital tissue and approximated herniated orbital tissue volumes in the (A) OF fracture group and (B) MW fracture group. Bars show means ± standard error. *Statistically significant ($P < 0.05$).

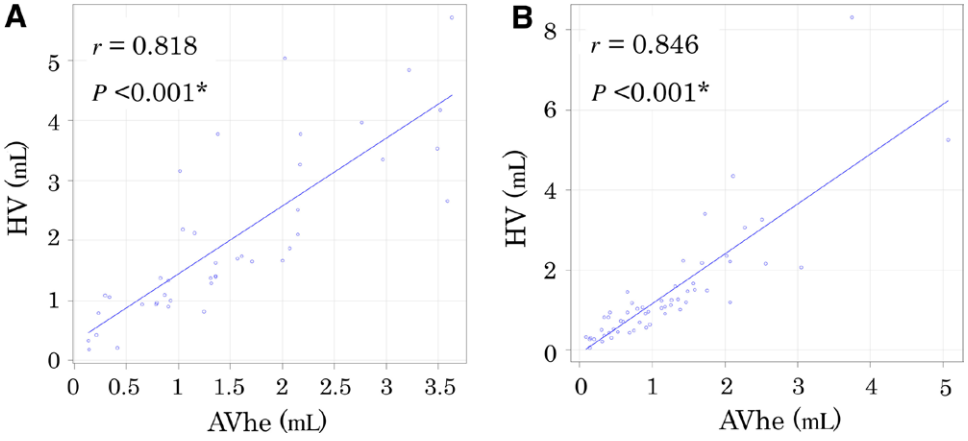

Fig. 4. Correlation between the degree of HV and volume approximated by assuming a hemiellipsoid shape in the (A) OF fracture group and (B) MW fracture group. *Statistically significant ($P < 0.05$).

Table 2. Bivariate Analysis of All Study Variables Versus the Volume of Herniated Orbital Tissue in the Orbital Wall Fracture Group

	HV ≤ 1.0 mL	HV > 1.0 mL	*P*
Sample size, n (%)	11 (26.2)	31 (73.8)	
Age, mean ± SD, y	39.5 ± 23.3	42.6 ± 19.4	0.672
Sex, n (%)			0.136
Men	5 (45.5)	23 (74.2)	
Women	6 (54.5)	8 (25.8)	
Fractures site, n (%)			0.485
Right	8 (72.7)	18 (58.1)	
Left	3 (27.3)	13 (41.9)	

Table 3. Bivariate Analysis of All Study Variables Versus the Volume of Herniated Orbital Tissue in the MW Fracture Group

	HV ≤ 0.9 mL	HV > 0.9 mL	*P*
Sample size, n (%)	21 (37.5)	35 (62.5)	
Age, mean ± SD, y	41.8 ± 26.9	43.1 ± 22.9	0.844
Sex, n (%)			1
Men	15 (71.4)	25 (71.4)	
Women	6 (28.6)	10 (28.6)	
Fractures site, n (%)			0.011*
Right	14 (66.7)	10 (28.6)	
Left	7 (33.3)	25 (71.4)	

*Statistically significant ($P < 0.05$).

69.2%, and AUC of 0.956 [95% confidence interval, 0.911–1]).

DISCUSSION

Numerous attempts have been made to clarify the relationship between specific CT characteristics at the time of injury and the degree of PE. With the availability of thin-slice CT and the widespread use of 3-dimensional image analysis software, the relationship between CT imaging characteristics and the degree of PE is being established. Many studies have mentioned the correlation between PE and HV. Jin et al[13] reported that HV of more than 0.9 mL was associated with PE of 2 mm or more in patients with blowout fractures of the medial orbital wall. In a study of patients with inferior blowout fractures, the HV threshold for visible PE was 1.0 mL.[23] Bouet et al[24] assessed the correlation between HV and incidence of late enophthalmos and found that each 1.0 mL increase in HV was accompanied by a 2 mm increase in enophthalmos.

However, HV measurements can be time-consuming, complicated to perform, and relatively impractical for routine use.[20] To determine the HV on CT, the area of herniation must be manually measured on a 2-dimensional image slice and multiplied by the slice thickness; then, these values must be summed across all slices that include the orbit. Although machine-learning algorithms have been developed to automate the measurement of orbital volume, they are not available for use in current versions of radiology imaging software.[18,25] The aim of this study was to identify a concise, reliable, and clinically applicable method for measuring HV.

We calculated the difference between HV and AVrp/AVqp/AVhe to compare the shape of herniated orbital

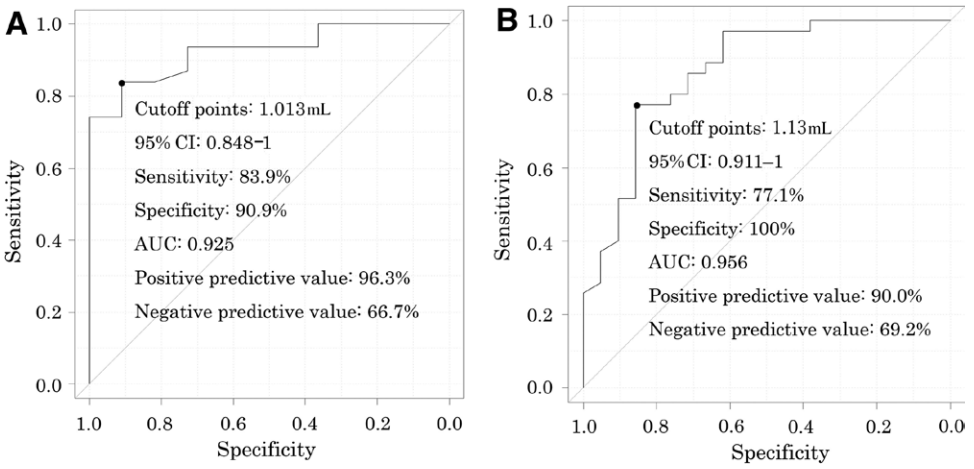

Fig. 5. ROC curves using volume approximated by assuming a hemiellipsoid shape to predict HV in the (A) OF group and (B) MW fracture group. CI, confidence interval.

tissue and the shape of approximated herniated orbital tissue. A difference close to zero indicated that the AV was approximately equal to HV. In both the OF and MW groups, the mean HV–AVhe difference was the closest of the 3 mean differences to 0, suggesting that AVhe provided the closest approximation to the shape of herniated orbital tissue. In both groups, the Pearson correlation analysis showed a positive linear relationship between HV and AVhe.

In the ROC curve analyses, the optimal AVhe cutoff value associated with high HV in the OF group (>1.0 mL) was 1.013 mL. In the MW group, high HV was defined as greater than 0.9 mL, and the optimal AVhe cutoff was 1.13 mL. The AUC values suggested excellent performance in both groups. The positive and negative predictive values in the OF group were 96.3% and 66.7%, respectively; in the MW group, they were 90.0% and 69.2%, respectively.

In summary, this study demonstrated that the approximate volume of herniated orbital contents, calculated as a hemiellipsoidal shape, can serve as a viable substitute for the conventional HV measurement method of manually tracing borders. However, in the MW group, the cutoff values for AVhe differed from HV because the morphology of the MW fracture is presumed to be more complex. This suggests that different cutoff values should be used when using AV as an alternative to HV.

This study demonstrated relatively high specificity and positive predictive values, and low sensitivity and negative predictive values in both groups. Higher specificity and positive predictive values indicate lower false positives. This suggests that patients with high AVhe are more likely to exhibit high HV. However, higher sensitivity and higher negative predictive value are desirable for a screening test. The lower-than-expected negative predictive value could potentially be improved by developing an algorithm that combines several tools, including AVhe.

This study has several limitations. Although the associations of AVrp, AVqp, and AVhe with HV were compared, and the hemiellipsoid shape provided the closest approximation to the shape of herniated orbital tissue, the shape of herniated orbital tissue varies in real-world clinical practice. Further prospective studies are necessary to demonstrate the clinical usefulness of AVhe. Furthermore, few patients underwent follow-up CT or Hertel exophthalmometry, and a direct comparison between PE and AV was not possible.

The timing of CT scan volumetry is important and controversial. Scolozzi et al[26] limited the assessment to the day of injury, whereas Choi et al[27] restricted it to within 1 week after injury. Because the degree of edema and fibrosis changes over time after orbital injury, it is necessary to establish standardized criteria for the timing of CT scan volumetry.

CONCLUSIONS

CT image analysis provides valuable data to assist in planning the appropriate treatment for blowout fractures of the orbit. Our simplified method, which approximately calculates the volume of herniated orbital contents in a hemiellipsoid pattern model, proved to be practical, easy, and more reliable than the conventional method.

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DISCLOSURE

The authors have no financial interest to declare in relation to the content of this article.

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