Overview of tools for the measurement of the orbital volume and their applications to orbital surgery

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REVIEW ARTICLE: Overview of tools for measurement of the orbital volume and their applications to orbital surgery

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ABSTRACT

There are numerous applications in craniofacial surgery with orbital volume (OV) modification. Careful management of the OV is fundamental to obtain good aesthetic and functional results in orbital surgery. With the growth of Computer-Aided Design – Computer-Aided Manufacturing (CAD-CAM) technologies, patient-specific implants and custom-made reconstruction are being used increasingly. Precise measurement of the OV before surgery is becoming a necessity for craniofacial surgeons. There is no consensus on orbital volume measurements (OVMs). Manual segmentation of computed tomography (CT) images is the mostly used method to determine the OV, but is time-consuming and very sensitive to operator errors. Here, we describe the various methods of orbital volumetry validated in the literature that can be used by surgeons in preoperative planning of orbital surgery. We also describe the leading software employed for these methods, and discuss clinical use (posttraumatic enophthalmos prediction, orbital reconstruction) in which OVMs are important.

KEYWORDS: orbital volume measurement; orbital surgery; pre-operative planning; enophthalmos; orbital reconstruction.

INTRODUCTION

Orbital volume measurements (OVMs) are invaluable tools for surgeons. There are numerous clinical applications in craniofacial surgery with orbital volume (OV) modification: posttraumatic enophthalmos correction, orbital reconstruction, or orbital decompression following thyroid-related orbitopathy. All of these surgical procedures can alter the position of the ocular globe within the orbit [1]. Computed tomography (CT) with multi-planar reconstruction is the reference imaging procedure for assessment of craniofacial injuries because it provides the best spatial resolution and analysis of osseous structures [2].

For decades, physicians have been measuring orbital structures in search of the predictive factors of enophthalmos after orbital fractures [3]. It is now well documented that an increase of 1 cm^3 in the OV is responsible for enophthalmos of 1 mm[4–6]. Enophthalmos is considered to be clinically visible if it is >2 mm [7]. Careful management of the OV is, therefore, fundamental to obtain good aesthetic and functional results in orbital reconstruction surgery. However, surgical indications are often selected based on the surgeon's personal experience without measurements on CT [2]. This approximation frequently involves globe malpositioning postoperatively.

With the development of Computer-Aided Design – Computer-Aided Manufacturing (CAD-CAM) technologies, patient-specific implants and custom-made reconstructions are being used increasingly [8]. It is becoming a necessity for craniofacial/orbital surgeons to measure the preoperative OV precisely in order to perform the best anatomic reconstruction of the orbit.

Currently, a consensus on OVMs is lacking. Manual segmentation of CT images is considered to be the "gold standard" to determine the OV. However, this method is time-consuming and very sensitive to operator errors [9]. Semi-automatic and automatic methods are available for OV analyses, but have their own strengths and weaknesses. The main problem related to OVMs is the delimitation of orbital boundaries. Conversely, surgeons need a reliable, reproducible, easy-to-use, rapid and ideally free access OVM method for everyday use.

The aim of this overview is, therefore, to present the various methods of orbital volumetry validated in the literature that can be used currently by surgeons in preoperative planning of orbital surgery.

METHODS OF ORBITAL VOLUME MEASUREMENT

Orbital volume measurements: historical background

For more than one century, scientists have been trying to develop a quantification method for the OV. The first OVMs were undertaken in the nineteenth century for anthropologic and anatomic purposes. As medical knowledge progressed, the analysis of OV has proven to be very useful in the study and treatment of traumatic, malformative, neoplastic, endocrine or vascular disorders affecting orbital growth [10].

In 1873 in France, Gayat was probably the first to publish OV data [11]. He filled the orbital cavity of 11 skulls with lead pellets and poured them into a graduated cylinder to determine the OV; he documented an average OV of 29 cm^3. Subsequently, other authors used the graduated cylinder method with different materials as orbital fillers: dry sand (after orbital bony lining with plasticine) [12], cellophane [13], or hard seeds [14].

In 1970, Sarnat [15] validated the use of casts to measure the OV. He filled rabbit orbits with an elastic rubber polymer, and the OV was calculated from the net weight and specific gravity of the material [11]. Sarnat used water displacement to determine the volume of the material. This method, based on Archimedean principles, is considered as the gold standard to determine OV. However this technique is not achievable *in vivo*.

During the 20th century, OVM on living patients became possible with the development of medical imaging techniques. The first OVM on a living patient was performed in the 1960's with manual evaluation of roentgenographic images[11]. In

1976, Abujamra [16] published a treaty of “radiovolumetry of the orbit” based on the correlation between manual measurements of orbital rim diameter from plain X-ray (Caldwell view), with OVM obtained with lead pellet standard. Even if his results were satisfying at the time, it seems impossible today to assess OV simply based on the measurement of the entrance diameter of the bony orbit.

With the advent of tomodensitometry, volume measurement of irregular object became possible [11]. Cooper [10] in 1985, established a method determining OV with CT scan applicable to living patients. He compared direct measurements with dry sand in skulls with OV obtained on CT sections (volume algorithm method) and found a discrepancy between the two methods ranging from 0.2% to 4%. In the same year, Forbes *et al.* [17] determined the volume of different components of the orbit with CT scan but using summation of pixels method. The accuracy of this technique was established at 7%-8% in comparison with measurements made on phantoms with water displacement method.

Since 1985, many authors tried to develop methods to determine OV with CT scan acquisitions. They compared their techniques to experimental methods (direct measurements like water displacement) to validate them and find the most accurate and reproducible method to determine OV [1,18,19].

Orbital volume measurements issues

The bone orbit is a four-sided pyramid, the base of which is anterior and open forward: the *aditus orbitalis*. It includes numerous foramina and fissures: the optic canal, superior orbital fissure, inferior orbital fissure, and nasolacrimal duct. Upon CT, the components of the orbital cavity are heterogeneous (muscles, fat, ocular globe, lacrimal gland), whereas the bony walls are very thin. Although CT technologies have become significantly more advanced, with higher-resolution images, the orbital cavity is not a closed cavity and bony walls are sometimes complex to identify (especially after trauma). Delimitation of the orbital cavity boundaries using CT is indeed difficult and may vary from one operator to another. It can lead to a lack of reproducibility, mainly in manual methods.

Review of the literature suggests that orbital volumetry studies are not comparable between each other. This is due, in particular, to significant differences in methodology and difficulties in determining the orbital limits in the CT image, especially the *aditus orbitalis* [11]. Since surgeons became interested in OVMs using medical imaging, they compared and validated new methods with these experimental methods. Nevertheless, an established consensus on the way to undertake OVMs is lacking.

Manual segmentation: planimetry

Planimetry is considered to be the most common method. It is based on the summation of the manually delineated areas obtained from a CT image [2]. The operator delineates the boundaries of the orbital bone cavity manually on a series of CT slices. The operator proceeds, section by section, in the axial plane, and fits the design in sagittal and coronal planes. The bony openings (foramina and fissures) are excluded because a straight line is drawn to cover them [11]. Management of the anterior boundary is dependent upon the researcher: either a straight line connecting the medial and lateral orbital rims or a line drawn along the cornea. The volume of the segmented orbital cavity is calculated based on the section thickness, area of the orbital cavity in section, space between slices, and total number of slices containing the region of interest (ROI) [2]. The accuracy is related directly to the number of slices.

Boundaries are defined by the operator and not by standard charts; this can be a source of errors with low reproducibility. The main weakness of planimetry is that, to be accurate, it is extremely time-consuming. The main advantage is that manual segmentation is available on all standard medical imaging softwares. In **Figure 1 and 2** we present an example of OVR measurement using planimetry.

Automatic methods

Automatic segmentation of the orbital cavity can be undertaken using a function integrated within software. This method relies on atlas segmentation. Only one method has been described in the literature for orbital volumetry, and has been associated with unsatisfactory results [9]. The main weakness of this method is the management of orbital fissures and foramina, which is handled poorly by software. However, these fully automatic techniques are extremely fast and are emerging and developing. They offer attractive images as shown in **Figure 3**.

Semi-automatic methods

A semi-automatic method is defined as a method using volumetric built-in functionality in software, combined with manual adjustments. Various semi-automatic methods are available, depending on the software used.

Some of these methods combine planimetry with the positioning of specific landmarks on the CT image [20] or use of selected ROI tools [21].

Stereology is one of these methods. Based on the fundamental principles of geometry (Cavalieri's principle) and statistics (sampling), stereology is the three-dimensional (3D) interpretation of 2D slices of a ROI or organ of interest (OOI). First, the operator chooses the number and orientation of slices (axial, coronal or sagittal), as well as the number of sampling points on the grid. Then, he/she selects sampling points on the grid on different CT-image sections. Assessment of many slices combined with regrouped and numerous sampling points are crucial for an accurate OVM*.* Stereological can be used to assess any organ volume with its coefficient of error by employing only a sample of slices containing the OOI [2].

MAIN SOFTWARE OF ORBITAL VOLUME MEASUREMENT

The different methods of orbital volumetry described in the literature are listed below and summarized in **Table 1**.

Mimics®

In 2000, Ramieri *et al.* used, for the first time, manual segmentation on Mimics® version 4.0 (Materialise, Leuven, Belgium) [3]. They analyzed the OV of 25 orbits treated for complex orbital fractures with 3D CT reconstruction. They confirmed that enophthalmos is correlated with the OV and the height of the orbital retrobulbar portion, but they did not validate their method.

In 2008, Regensburg *et al.*, validated this planimetry method on Mimics® version 9.11. They compared the volume of different components of a phantom (dry skull with butter and chicken muscles) obtained on CT with the already known volume of the structures (which were weighed before phantom manufacture). There was no significant difference between the two methods. They also compared the volumes of soft tissues taken from 10 CT examinations of human orbitals. The intraobserver and interobserver variabilities of these measurements were acceptable [22].

OsiriX MD®

In 2015, Shyu *et al.* assessed the normal OV in 20 Taiwanese patients using OsiriX MD® (Pixmeo, Geneva, Switzerland) [21]. They presented two methods of volume calculation based on 3D volume rendered-assisted ROI computation. The first method consisted of points positioned on the orbital rim of the reconstructed 3D craniofacial CT image. All these points created a plan that delimited the anterior part of the orbital cavity. Then, manual segmentation was realized on the 2D axial view to delineate the remainder of the orbital boundaries facilitated by use of a closed polygon ROI tool. The OV was calculated automatically by addition of all the selected regions, and a 3D volume rendered object was reconstructed.

The second method followed the same process except that the anterior limit was defined by the bicanthal line. The intraobserver and interobserver variabilities of OV calculations for both methods were found to be acceptable.

The second method was faster because it did not require 3D reconstruction and a 3D point assistance tool. However, it was less accurate because it did not account for a significant antero-medial portion of the orbit. Therefore, OsiriX MD® seems to be easy to use preoperatively but the authors did not validate their methods by comparing them with those of the gold standard. Moreover, OsiriX MD® is available only on Mac OS® (Apple, Cupertino, CA, USA).

iPlan®

In 2016, Jansen *et al.* [9] validated a semi-automatic segmentation method for OV analyses using iPlan® version 3.0.5 (Brainlab, Feldkirchen, Germany). First, they validated the manual segmentation as the gold standard (defining precisely the anterior boundary). Then, they compared three different methods to planimetry of one unaffected orbit in 21 CT examinations. The automatic method consisted of an automatic function integrated into iPlan®. It was not sufficiently accurate, with a difference of 0.49 cm^3 (SD 0.74) compared with planimetry, which was probably due to overestimation of the inclusion of surrounding tissues. The semi-automatic method combined the automatic method with subtraction of bone and air density masks. Compared with manual segmentation, the volume difference was low (0.24 cm^3; SD 16.0), but this method was more time-consuming (146 seconds) than the automatic method (38 seconds). The third method was similar to the semi-automatic method but was combined with manual adjustments. The “smart shaper” tool and eraser were used and adjustments made on bony boundaries. Unfortunately, it provided a lower accuracy, due to underestimation, with a mean difference of 0.86 cm^3 (SD 0.27) combined with a longer average time (327 s). According to the authors, the semi-automatic method seems to be the more accurate, reproducible, quick and easy to use.

Analyze®

In 2003, Koppel *et al.* assessed the OV on five dried skulls with a prosthetic globe by comparing the thresholding method on Analyze® (AnalyzeDirect, Overland Park, KS, USA) to the gravimetric water displacement method (gold standard) [1]. The thresholding method consisted of inserting manually the Hounsfield number of the prosthetic globe; then, the Analyze® calculated automatically the volume from these data. The results obtained varied from the gold standard by 0.06-50.44 % with a mean error of 8.8%. Hence, the accuracy was low, which was why this method was not retained for clinical use by the authors.

More recently, Bontzos *et al.* [2] used Analyze® to compare three methods for OV calculation on orbits from sheep and humans: planimetry, stereology, and water filling. Water filling measurements were used as the validation method. For stereology, the operator marked sample points of the ROI from a grid on CT slices. This required only a few representative sections, from which the 3D organ could be extrapolated statistically. With CT slices of 1 mm, they used 1/8 sampling (the minimum number of CT slices required) for stereology-based estimation because it was considered to be the optimal and time efficient approach. In sheep, results between the water filling method and stereology were correlated highly ($r = 0.893$; $p = 0.001$) but showed a significant difference on the paired Student's t-test ($t = 3.047$; $p = 0.014$). Between planimetry and the water filling method, the correlation was high ($r = 0.957$; $p = 0.001$) but there was no statistically significant difference ($p = 0.154$). In human subjects, results between planimetry and stereology were highly correlated ($r = 0.909$; $p = 0.001$). According to the authors, stereology was comparable with planimetry in terms of accuracy and was less time consuming (2.1 ± 0.1 min).

Maxillo®

In 2013, Strong *et al.* evaluated the accuracy and efficiency of Maxillo® (Stratovan Corporation, Davis, CA, USA). Maxillo® is a specific semi-automatic application for OV computation [20]. The OV was calculated automatically after the user placed six predefined anatomic landmarks (orbital rims, optic canals, external auditory canals) on the 3D craniofacial reconstructed CT image. The intraoperator error and interoperator error were low: 0.08 cm^3 (95 % confidence interval (CI), 0.06-0.10) and 0.18 cm^3 (95%CI, 0.14-0.20) respectively. To analyze the inter-image variability, the authors performed CT examinations of the same orbits with different

CT devices at different times. They found large errors from 0.01 cm^3 to 1.53 cm^3 with no statistically significant differences due to the small sample size. The analysis of one orbit was rapid and took 138 seconds (SD = 24; range, 95-217). Moreover, Maxillo® can be used by a single operator. The measurements were accurate, with errors <0.1 cm^3. However, the authors did not compare this software with the gold standard.

DISCUSSION

Different methods of OVM are validated but there is no consensus on any of them. There are different clinical applications where the knowledge of OV can be very useful.

To predict posttraumatic enophtalmos

Orbital fractures often lead to early or late enophthalmos due to OV expansion. Posttraumatic enophthalmos is measured on a CT image (axial plane) by comparing the position of the ocular globe and a line drawn between each lateral canthi. This plan is not always easy to find and OVMs seem to be the best way to assess enophthalmos [5]. ~~This measurement must be performed in the neuro-ocular plane to avoid false findings. However, this plane is not always easy to find, especially in the posttraumatic context, where the position of the ocular globe can be modified not only in the anteroposterior plane but also in the craniocaudal plane. OVMs, which encompass both planes, seem to be the best way to assess enophthalmos [5].~~ Orbital volumetry has been used for direct comparison, orbital volume ratio (OVR) calculation, or for measurement of the volume of herniated soft tissue. Most authors have calculated the OV using manual segmentation.

Several studies have shown a correlation between an increased OV and enophthalmos [4–6,23–27]. Using planimetry, Whitehouse *et al.* showed that enophthalmos increased by 0.8 mm per 1 cm^3 of OV expansion [4], whereas Raskin *et al.* revealed that it increased by 0.47 mm per 1 cm^3 of OV expansion [24]. Sugiura *et al.* showed that enophthalmos of 2.0 mm corresponded to an increase in the OV of 2.25 cm^3 [25]. More recently, Mohajerani *et al.* also found a predictive power of 61.7% of the

OV for enophthalmos using a semi-automatic method [26]. Although the OV is considered to be predictive of long-term symptoms by most of authors, other scholars have not found a significant long-term linear correlation between an increased OV and enophthalmos [28]. Choi *et al.* pointed out that the OV is not a reliable measure to estimate the size of enophthalmos because of inter-individual variations in the OV [29]. However, almost perfect agreement of OV assessment between different readers using manual segmentation has been documented, suggesting that OVMs are reproducible and reliable [30]. Other scholars have suggested that the OV is susceptible to be overestimation (by between -1.8 mL and 2.6 mL) and should be interpreted with caution [31].

The OVR is the ratio between the traumatized orbit and the unaffected side: OVR (%) = (volume of the traumatized orbit / orbital volume of unaffected orbit) x 100. The OVR standardizes the variability of the OV and, thus, has good predictive value [29]. Several studies have shown a correlation between the OVR and enophthalmos in orbital fractures [29,32–35] . Using planimetry, Choi *et al.* showed that enophtalmos increased in proportion to the OVR, highlighting that an OVR of 112.18% induced enophtalmos of 2 mm [29]. Yang *et al.* found that an OVR of 106.85% led to enophthalmos of 2 mm [35]. Nevertheless, in some cases, the OVR cannot be measured reliably (e.g., bilateral orbital fractures). A variation in size between both orbits of the same patient has been documented, leading to misinterpretation of the true size of the fractured orbit [35]. A difference in the OV of 8% between the normal volumes of both orbits of the same patient has been recorded [17,36] but, in most cases, this difference is not significant [37]. ~~In **Figure 1** we present an example of OVR measurement using planimetry.~~

~~The volume of herniated soft tissues can also be used to predict enophthalmos. It is defined as orbital tissue herniated from the fracture edges of the orbital floor into the maxillary sinus (but not including the hematoma underneath the herniated orbital soft tissue in the maxillary sinus). Usually, the ratio of the volume of herniated soft tissues is obtained by dividing the volume of herniated muscle or fat by the OV and then multiplying by 100. Then, it is expressed as a percentage of the OV. Usually, planimetry is employed to measure the volume of herniated soft tissue, but semi-automatic methods have also been proposed. Zhang *et al.* showed a significant correlation between the volume of herniated orbital content and enophthalmos using Mimics® version 8.11. It was found that only the herniated tissue posterior to the equator of the ocular globe was important. Using manual segmentation, Jin *et al.* showed that enophthalmos of 2 mm occurred if the volume of herniated soft tissue was >0.9 mL. Ploder *et al.* found that a volume of displaced tissue of 1.89 ± 1.19 mL was correlated with enophtalmos of ≥2 mm. In fractures of the medial orbital wall, Choi *et al.* identified enophthalmos as being positively correlated with the volume of herniated muscle and fat, whereas it was correlated only with the volume of herniated fat in fractures of the inferior orbital wall. Irrespective of the method used to obtain volume of herniated soft tissue, there is no consensus on the threshold that induces significant enophthalmos, probably due to an insufficient number of patients in these studies. For some scholars, the correlation between the herniated OV and relative difference in the OV between orbits was poor. According to Yang *et al.*, the OVR was more reliable than the volume of herniated soft tissue using planimetry with 3D Workstation® (TeraRecon, Foster City, CA, USA).~~

To plan a surgical intervention

Orbital volumetry, therefore, offers good characterization of enophthalmos, which is necessary to: determine the size of implants or grafts; improve accuracy and reduce the duration of surgical procedure [38–43]. Enophthalmos and dystopia are challenging conditions with often-poor surgical results necessitating several surgical interventions if undertaken free-handedly. If the reconstruction is extended to the zygomatic complex, the surgical challenge increases [44].

Orbital volumetry is indeed necessary to confirm postoperative success. Rana *et al*. in 2015, compared OV of 34 cases of primary reconstruction of unilateral orbital fractures treated using selective laser-melted patient specific implant or pre-bent titanium mesh [45]. The post operative difference in volume between the unaffected and the reconstructed orbit was lower in the specific implant group and this difference of volume differed significantly between the 2 groups. Kim *et al.* in 2018 found a significant decrease of the OVR in patients who had undergone orbit reconstruction with patient specific implants [46].

Reconstruction based on the anatomy of the unaffected side has been developed and proved to be accurate [45]. So OV is also useful to determine the surgical objective and to design cutting guides and implants using mirroring method on the healthy side. Sozzi *et al.* used manual planimetry [47], whereas Wi *et al.* used the Eclipse Treatment Planning System® version 13.0 (Varian Medical Systems, Palo Alto, CA, USA) [48] to assess their results for posttraumatic enophthalmos correction. Fan *et al.* used manual planimetry and mirroring to define the size of the implant (hydroxyapatite sheets or autogenous rib grafts) used to treat posttraumatic enophthalmos, and obtained better results than with standard implants [43]. Lieger et *al.* evaluated use of CAD-CAM in late reconstruction of orbital fractures employing inhouse software with a mirroring method [38]. Enophthalmos was corrected in all patients and diplopia was reduced in half of the patients. Pedemonte *et al.* studied the accuracy of reconstruction with customized implants [40]. Two methods were used to manufacture implants: wax-casting (using a stereolithographic model sent to the laboratory for modelling) and CAD-CAM with mirroring. After surgery, the volume of the affected orbit was reduced by 8.55%, and diplopia and enophthalmos were corrected in most cases. Zimmerer *et al.*, in a prospective study of 195 patients with orbital fractures, showed significantly more accurate reconstruction of the OV with custom-made implants *versus* standard preformed implants using mirroring and iPlan CMF® version 3.0.5 [41]. Gander *et al.* used the same software to design patient-specific implant to reconstruct orbital walls, and obtained accurate results [49]. For some authors, the median time of the surgical procedure was also shorter if personalized implants were employed [41,50]. For Klein *et al.*, CAD-CAM was a very accurate method to correct severe enophthalmos after the primary surgical procedure [51].

Virtual surgical planning, as well as customized cutting guides and plates, are being used increasingly to enhance accuracy and efficiency in complex orbital and zygomatico-orbital [44,52] or cranio-orbital surgery, such as box osteotomies or facial bipartition [53,54]. They use mirroring, so the OV is restored precisely. Orbital volumetry is necessary to define precise objectives in orbital reconstruction. These are needed for the design and manufacture of custom-made cutting guides and implants, which will offer perfectly accurate result. ~~We offer some examples of OVM through **Figures 2 and 3.**~~

~~*Orbital volumetry in thyroid-related orbitopathy*~~

~~Thyroid-related orbitopathy (mostly Graves' orbitopathy (GO)) is responsible for exophthalmos due to an increase in the volume of orbital soft tissue as a result of muscle volume (MV) increase or fat volume (FV) increase or a combination of both. Assessment of soft tissue volume requires OVMs to obtain MV:OV and FV:OV ratios. Planimetry, as described by Regensburg *et al.,* was used by Regensburg *et al.* and Wiersinga *et al.* to determine which soft tissue was affected by GO. They were able to define four groups of patients (as hypothesized by Zonneveld *et al.*): no increase in the FV or MV; increase in only the FV; increase in only the MV; increase in the FV and MV. Correct definition of each group of patients is important because it has therapeutic consequences. Several methods of orbital decompression are used because no clinical trials have demonstrated clear superiority of one method over the other. Being able to characterize precisely between muscle and/or fat involvement using orbital volumetry could aid allocation of patients to each group, and define the indications for fat removal or bone removal, or a combination of both.~~

~~Orbital volumetry can also be used to assess treatments outcomes for thyroid-related orbitopathy. Li *et al.* used manual planimetry to evaluate the efficacy of rituximab associated with ^{131}I in treatment of GO with hyperthyroidism. Schiff *et al.* used semi-automated segmentation with OsiriX MD® to measure changes in the OV after medial and inferior orbital decompression. Orbital volumetry offers an objective assessment and, because access to easy and reproducible methods of OVMs are being developed, it will be employed frequently as a primary outcome assessment in the future.~~

Orbital volume measurement: essential tool?

OVM is a precious tool to predict enophtalmos and to plan an orbital surgery using CAD-CAM technologies. We need a quick technique, easy to use, reproducible, ideally and available for all orbital surgeons. Unfortunately, OVM method is not consensual.

We have to keep in mind that after a trauma of the orbit, or after an orbital surgery, retraction of the periorbital tissues can involve enophtalmos even if the volume of the bony orbit is restituted or respected. The restoration of the OV is therefore essential but is not the only factor to be taken into account. However, according to Bite *et al.* [5], in the majority of patients, the cause of posttraumatic enophthalmos is increased bony orbital volume rather than by soft-tissue loss or fat necrosis.

CONCLUSION

OVMs are becoming necessities in the era of virtual surgical planning and patient-specific orbital reconstruction and implants. OVMs are also useful for prediction of posttraumatic enophthalmos ~~and to manage thyroid-related orbitopathy~~.

Several methods and software types have been developed to measure the OV. Planimetry remains ~~the gold standard~~ the mostly used but various semi-automatic and automatic methods of OVMs are emerging from imaging software, which will probably, as their accuracy increase, become essential.

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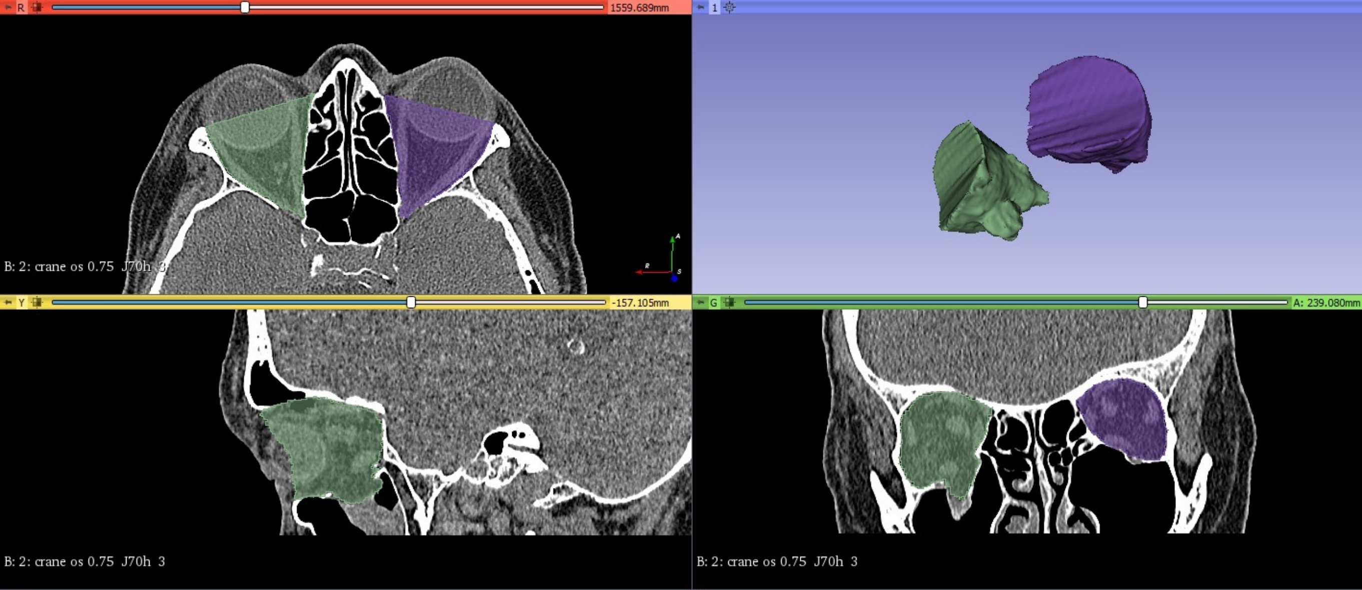
TABLES AND FIGURES

Fig. 1: Screenshot of OVR measurement of an orbital blowout fracture with planimetry method using 3D slicer software (version 4.10.2). The OVR is obtained by 3D reconstruction with volume rendering technique (112.14%).

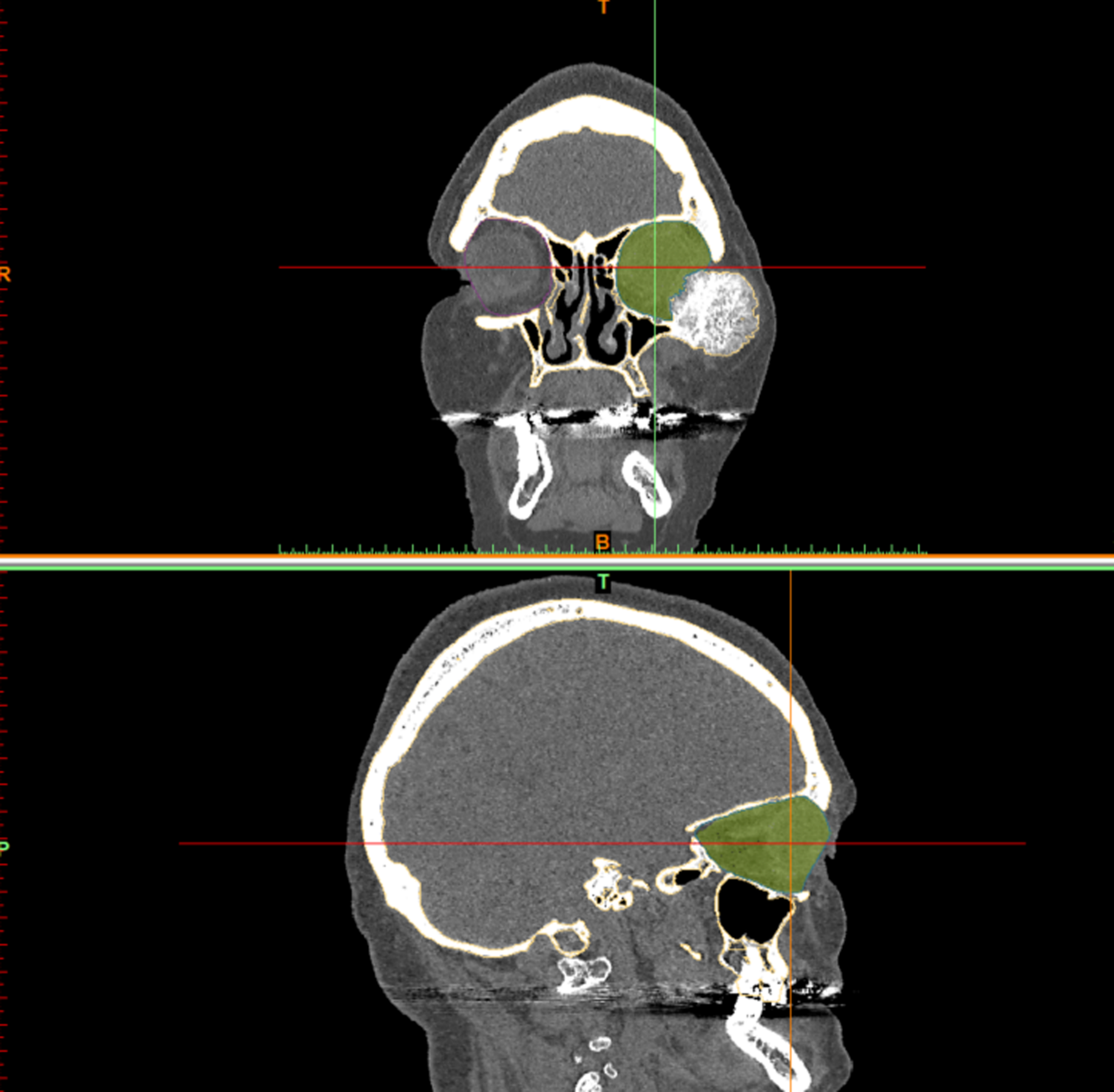
Fig. 2: Example of orbital volumetry with Mimics® version 4.0 (Materialise, Leuven, Belgium) as part of orbital reconstruction plan of a benign bone tumor. The method used is planimetry. **a**- Axial and coronal sections during manual segmentation process. **b**- Axial section of normal left orbit during manual segmentation process. **c**- Axial section of reduced right orbit during manual segmentation process. **d**- 3D reconstruction. **e**- Frontal view of both volume-of-interest. **f**- Oblique upper view of both volume-of-interest.

Fig. 3: Example of orbital volumetry of the same patient as Fig.2 with iPlan CMF Planning software (Brainlab AG, Bonn, Germany). An automatic segmentation is realized based on anatomical atlas. Manual adjustments are possible when needed. Specific objects corresponding to anatomical or surgical structures can be selected. **a**- Axial section after automatic segmentation. **b**- 3D reconstruction with all the objects segmented selected. The orbital volume left appears in yellow. **c**- 3D reconstruction of orbital areas without orbital globes. **d**- 3D reconstruction of orbital areas with orbital globes.

Table 1: Different methods of orbital volumetry currently described in the literature.



Segment	Number of voxels [voxels]	Volume [mm3] (1)	Volume [cm3] (1)	Surface area [mm2]	Volume [mm3] (2)	Volume [cm3] (2)
Segment_1	338710	27415.3	27.4153	5657.75	27487.9	27.4879
Segment_2	302008	24444.6	24.4446	5137.79	24513.2	24.5132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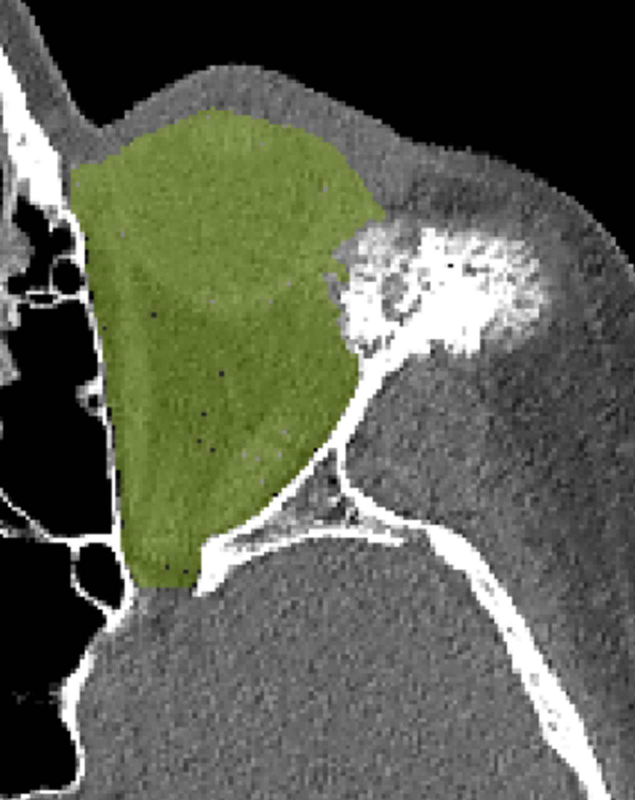

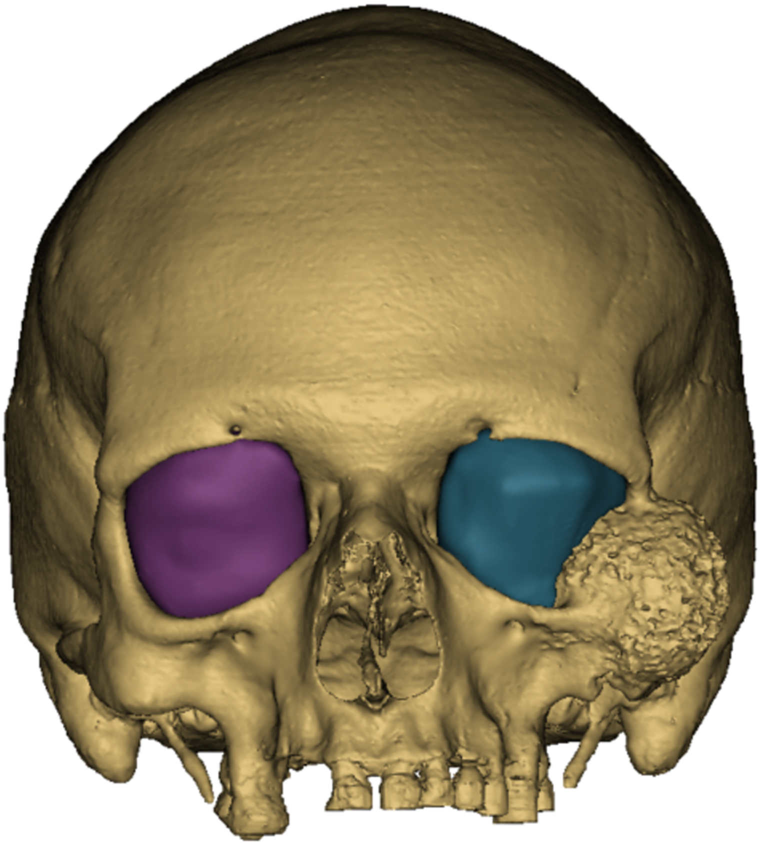

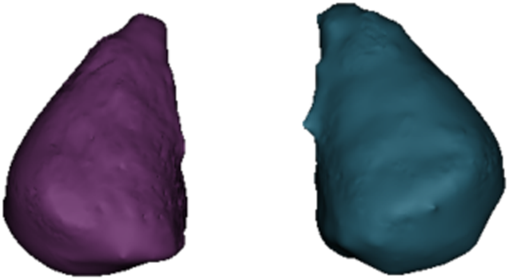

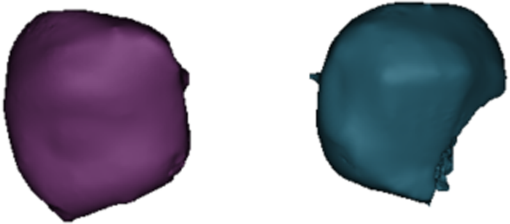

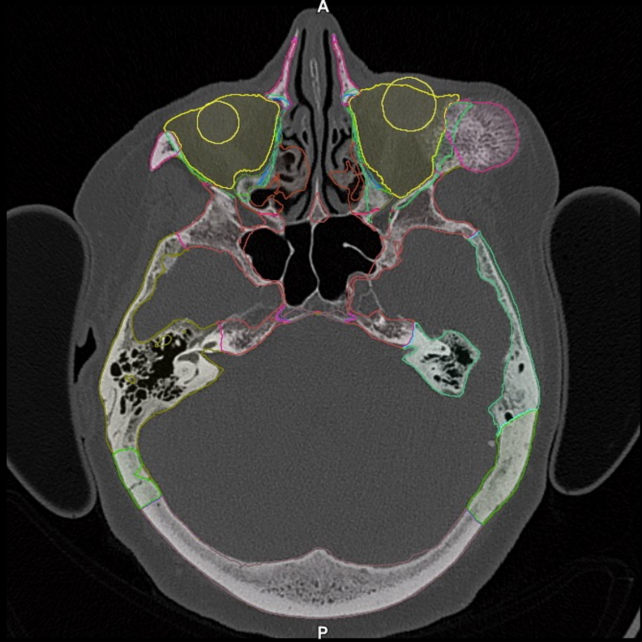
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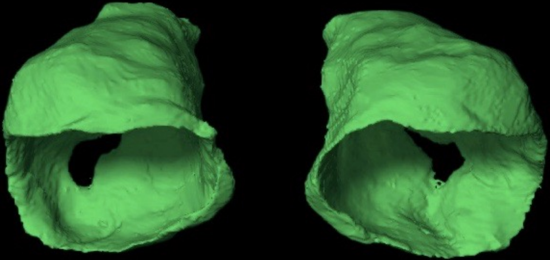

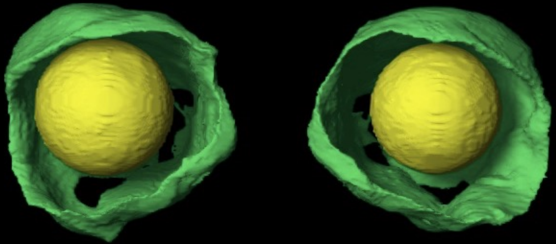

SOFTWARE	AUTHORS, YEAR	OVM METHODS	COMPARISON METHOD	RESULTS	ADVANTAGES / DISADVANTAGES
Mimics® 4.0 Materialise, Leuven, Belgium	Ramieri *et al.* [3] 2000	Planimetry 25 orbits treated for complex orbital fractures with 3D CT reconstruction	/	Enophthalmos is correlated with the OV and the height of the orbital retrobulbar portion	They did not validate their method
Mimics® 9.11 Materialise, Leuven, Belgium	Regensburg *et al.* [22] 2008	Planimetry Volume of different components of a phantom (dry skull with butter and chicken muscles)	Volume of the structures of the phantom which were weighed before phantom manufacture	No significant difference between the two methods	Did validate planimetry method with acceptable intraobserver and interobserver variabilities
OsiriX MD® Pixmeo, Geneva, Switzerland	Shyu *et al.* [21] 2015	Planimetry Plan manually created along orbital rim versus bicanthal line to demarcate the anterior part of the orbital cavity	/	Bicanthal line: faster, but less accurate than 3D point assistant tool Intra/interobserver variabilities of OV for both methods were found to be acceptable	Available only on Mac OS® Easy to use preoperatively Did not validate their methods by comparing them with those of the gold standard
iPlan® Brainlab, Feldkirchen, Germany	Jansen *et al.* [9] 2016	Automatic method (A) Semi-automatic method (SA) Semi-automatic method with manual adjustments (SAA)	Validation of manual segmentation (MS) as gold standard (defining precisely the anterior boundary)	A : not accurate compared to MS 0.49 cm^3 (SD 0.74) SA : accurate 0.24 cm^3 (SD 16.0), but time consuming (146 sec) SAA : lower accuracy 0.86 cm^3 (SD 0.27) combined with a longer average time (327 s)	The semi-automatic method (SA) seems to be the more accurate, reproducible, quick and easy to use.
Analyse® AnalyzeDirect, Overland Park, KS, USA	Koppel *et al.* [1] 2003	The thresholding method on Analyze® OV on five dried skulls with a prosthetic globe	Gravimetric water displacement method	Varied from the gold standard by 0.06-50.44 % (SD 8.8%)	Not retained for clinical use by the authors

Analyse® AnalyzeDirect, Overland Park, KS, USA	Bontzos *et al.* [2] 2018	Planimetry and Stereology OV calculation on orbits from sheep and humans	Water filling method as validation method	Sheep: water filling method vs stereology correlated highly ($r = 0.893$; $p = 0.001$) but showed a significant difference on the paired Student's t-test ($t = 3.047$; $p = 0.014$). Planimetry vs water filling method, correlation was high ($r = 0.957$; $p = 0.001$) but there was no statistically significant difference ($p = 0.154$). Human : planimetry and stereology were highly correlated ($r = 0.909$; $p = 0.001$).	According to the authors, stereology was comparable with planimetry in terms of accuracy and was less time consuming (2.1 ± 0.1 min).
Maxillo® Stratovan Corporation, Davis, CA, USA	Strong *et al.* [20] *2013*	Semi-automatic OV calculated automatically after the user placed six predefined anatomic landmarks on the 3D craniofacial reconstructed CT image	/	The intraoperator error and interoperator error were low: 0.08 cm^3 (95 % confidence interval (CI), 0.06-0.10) and 0.18 cm^3 (95%CI, 0.14-0.20) respectively. Analysis of one orbit was rapid and took 138 seconds (SD = 24; range, 95-217). The measurements were accurate, with errors <0.1 cm^3	The authors did not compare this software with the gold standard.