

# Blowout fractures - clinic, imaging and applied anatomy of the orbit

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This review has been accepted as a thesis together with four original papers by University of Copenhagen 18<sup>th</sup> of December 2017 and defended on 11<sup>th</sup> of January 2018.

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Dan Med J 2018;65(3):B5459

The four original papers are:

- I. Felding UA, Rasmussen J, Toft PB, von Buchwald C. The functional outcome of blow-out fractures managed surgically and conservatively: our experience in 100 patients. *Eur Arch Otorhinolaryngol.* 2016 Jul;273(7):1927-31.
- II. Felding UA, Bloch SL, Buchwald Cv. The Dimensions of the Orbital Cavity Based on High-Resolution Computed Tomography of Human Cadavers. *J Craniofac Surg.* 2016 Jun;27(4):1090-3.
- III. Felding UA, Damgaard OE, Bloch SL, Darvann TA, Thomsen C, Toft PB, von Buchwald C. Blowout fractures: Longitudinal Magnetic Resonance Imaging of post traumatic changes. Submitted.
- IV. Felding UA, Karnov K, Clemmensen A, Thomsen C, Darvann TA, von Buchwald C, Tranum-Jensen J. An applied anatomical study of the ethmoidal arteries: Computed Tomographic and direct measurements in human cadavers. *J Craniofac Surg.* 2018 Jan;29(1):212-216.

## OBJECTIVES

Isolated fractures of the orbital walls, or BOFs, may lead to functional disorders of the visual apparatus and aesthetic deformity. Debilitating double vision and facial disfiguring due to an altered position of the eye may affect patients' daily living skills and quality of life and they may find it difficult to perform important aspects of daily life, for instance, working or driving.

The management of these fractures is often challenging, since not all fractures demand surgery, as some patients may have symptoms which subside or may never develop symptoms. Due to a lack of evidence there are still considerable differences in opinion regarding the criteria for surgery. Selection for surgery depends on a thorough multidisciplinary clinical examination and an evaluation of the orbital damage on a computed tomography (CT) scan. Objective imaging parameters combined with a valid clinical examination are essential for surgical decision-making and the selection of patients for surgery is crucial.

Knowledge relating to the causes of double vision and enophthalmos is essential to improve patient outcomes. The physical forces resulting in a blowout fracture of the orbit produce soft-tissue damage in addition to the bony fractures. An intraorbital edema may lead to detectable changes in orbital morphometrics. When measuring the human orbit, most studies rely on the similarity of the contralateral orbit for comparison. However, the orbits may not be symmetrical with regards to all morphometrics.

Knowledge of the anatomy is important for safe orbital surgery. Knowing the location of arteries in the orbit is pivotal to avoid iatrogenic damage. The distance from the anterior lacrimal crest to the ethmoidal arteries and the optic canal in the orbit have traditionally been characterized by the 24-12-6 mm rule of thumb but preoperative measurements on CT images may provide more precise distances than absolute rules<sup>1</sup>.

The primary objectives of this thesis are:

- 1) To assess the current treatment of blowout fractures at the Departments of Otolaryngology and Ophthalmology, Rigshospitalet (Paper I)
- 2) To study the anatomy of the orbital cavity including the pathophysiology of blowout fractures:
  - (a) To investigate the 24-12-6 mm rule of thumb regarding distances from anterior landmarks to the ethmoidal arteries and the optic canal in the orbit and assess the potential role of computed tomography in estimating these distances (Paper IV)
  - (b) To investigate the supposed symmetry between the left and right orbit in the same person with regards to orbital morphometrics (Papers II, III and IV).
  - (c) To determine the extent of edema in the intra-orbital soft tissue in the initial post traumatic days in patients with blowout fractures using Magnetic Resonance Imaging (Paper III)

## BACKGROUND

### ANATOMY OF THE ORBITAL CAVITY AND ITS CONTENTS

#### Orbital bones

The orbit is a pyramid-shaped cavity in the skull, which contains a complex array of structures serving visual function. The apex is situated proximally while the base opens onto the facial skeleton. The surrounding paranasal sinuses develop as pneumatization processes in bone<sup>2</sup>. The orbital cavity, however, is the result of the development of seven embryologically distinct bones: maxilla, frontal, zygomatic, palatine, lacrimal, ethmoidal and sphenoid (Fig. 1A-C). The bony orbit forms as mesenchyme encircles the optic vesicle six weeks into the embryonic stage. The bony orbit develops as the individual bones ossify around the evolving optic cup and stalk.

The orbit has four walls: the floor, the roof and the medial and lateral walls. The roof, formed by the frontal bone, separates the anterior cranial fossa from the orbit. Supraorbital ethmoidal cells which separate the orbit from the anterior cranial fossa are not, however, uncommon<sup>3</sup>. The lateral wall is thick and is formed by the zygomatic and sphenoid bones. The medial wall, formed by the frontal, ethmoidal and lacrimal bones, and orbital floor, formed by the maxillary and sphenoid bones, are thin walls, which separate the orbit from the ethmoid and the maxillary sinus, respectively.

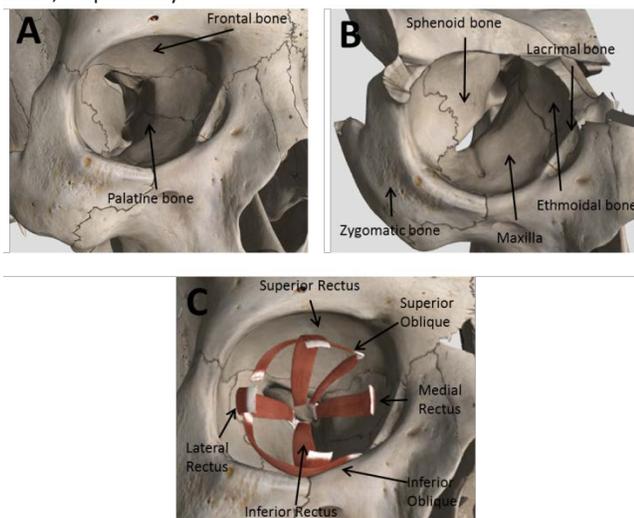


Figure 1. The bony orbit. 1A shows the bony orbit from an anterior-lateral angle. Suture lines separate the seven orbital bones. 1B shows the orbit from above with the frontal bone removed. 1C shows the bony orbit and the six extraocular muscles (EOMs) (all figures adapted from 3D4Medical.com with permission).

#### Orbital fat tissue

The structure of adipose tissue in the body is composed of fat cells contained within fat lobules, which are within fat pearls, which are contained within fat sections, which are within fat compartments<sup>4</sup>. The fat lobule is the smallest grouping of fat cells; it is supplied by its own neurovascular bundle and is surrounded by a thin connective tissue membrane. The adipose tissue in the orbit is different from omental and subcutaneous fat in that the orbital fat cells are organized into smaller fat lobules<sup>5</sup>. This results in a greater proportion of interlobular connective tissue per given volume of fat, which may explain why orbital fat

appears softer and more compliant than body fat<sup>6</sup>. This may facilitate the orbital fatty tissue functioning as a physical shock absorber for the globe in both traumatic conditions as well as in normal conditions during eye movements<sup>7</sup>. Structurally and bio-chemically, there are no regional differences in the orbital fat<sup>8</sup>.

The knowledge of orbital lymphatic physiology is currently still limited. Lymphatics are clearly present in some areas of the orbital cavity, for example, the lacrimal gland and the conjunctiva. Some studies have failed to find lymphatic vessels in the orbital fat and muscle<sup>9,10</sup> while others have found indications of lymphatic vessels in small areas of the muscles<sup>11</sup>. With the advent of recent advances in vascular markers, it is likely that, in the near future, studies will be able to prove whether or not other orbital tissues such as the extraocular muscles and posterior orbital fat also possess a lymphatic system<sup>12</sup>.

#### Extraocular muscles

Six extraocular muscles are attached to the globe and control its movements (Fig. 1C). The four rectus muscles arise from a ring-formed fibrous band called the annulus of Zinn posteriorly in the orbit. The muscles run anteriorly and insert into the sclera past the equator of the globe. The lateral and medial muscles abduct and adduct the eye, respectively. The main function of the inferior and superior rectus is to depress and elevate the eye. There is also some torsional and horizontal movement due to the angle between the muscle plane and the visual axis. The superior oblique muscle originates superior to the annulus of Zinn. It runs along the medial wall where its tendon slides through the trochlea and turns laterally and inserts into the sclera on the superoposterior side of the eye. Its function is the intorsion, depression and abduction of the eye. The inferior oblique muscle originates anteriorly from the maxilla and passes laterally and posteriorly to insert on the inferoposterior surface of the globe producing extorsion, elevation and abduction of the eye.

#### Orbital connective tissue

The extraocular muscles and the fat tissue are separated into compartments by connective tissue, which forms a framework. These tissue septa are aligned with directions of force and resist displacement of extraocular muscles during contraction<sup>13</sup>. The septa maintain muscular alignment and minimize vector shifts and side-slip over the globe during eye movement<sup>13</sup>. The various muscles' sheaths are connected by intermuscular septae, which are irregularly placed in the orbit. There is no connecting circular septum dividing the extra- and intra-orbital spaces.

Double vision following trauma leading to a blowout fracture may partly be due to the herniation of orbital fat and connective tissue into the surrounding sinus with subsequent traction on the muscle sheaths<sup>14</sup>. The extensive connective tissue septal system involves all orbital structures, including the globe, periorbita, optic nerve and extraocular muscles. Therefore, damage in any one portion of this system thus influences the whole system<sup>13</sup>. The periorbita is loosely adherent to the orbital bone while the inner surface of the periorbita is continuous with the transorbital septal systems.

The arterial supply to the orbit comes from the internal carotid artery through the ophthalmic artery. The ethmoidal arteries arise from the ophthalmic artery, which enters the orbit through the optic canal and then courses along the medial wall giving off first the posterior ethmoidal artery and then the anterior ethmoidal artery. Both arteries enter their respective ethmoidal foramina in the medial wall. Knowledge of the location of these

arteries is very important in avoiding iatrogenic damage, which may lead to an expanding orbital hematoma with a risk of loss of sight. Several situations in sinonasal surgery and orbital surgery warrant a knowledge of the arterial anatomy, for instance, accidental lesions of the arteries in sinus surgery may cause the arteries to disappear into the orbit, ethmoidal artery ligation due to either epistaxis or cutting the blood supply to a tumor before removal. Another situation is transorbital surgery with access to the anterior skull base through the medial wall, which is being performed increasingly frequently<sup>15</sup>.

The 24-12-6 mm rule characterizes the distance from the anterior lacrimal crest to the ethmoidal foramina and the optic canal in the orbit. This rule originates from a paper from 1979 on 24 Indian skulls with mean values of 24, 36 and 42 mm from the anterior lacrimal crest to the anterior ethmoidal foramina, posterior ethmoidal foramina and to the optic canal<sup>1</sup>. Measuring from the anterior lacrimal crest preoperatively is, however, difficult, since access to the medial wall is generally performed via a transcaruncular incision with dissection behind the lacrimal sac. The first bony landmark reached is thus, instead, the posterior lacrimal crest.

### BLOWOUT FRACTURES

Isolated fractures of the orbital walls without involvement of the orbital rim are often referred to as 'blowout' fractures. Floor fractures were first described by MacKenzie in 1884<sup>16</sup>. The term blowout fracture was first used in 1957 by Smith and Converse, who reproduced the fractures in cadaver experiments<sup>17,18</sup>. Three different theories have been proposed as the trauma mechanism (Fig. 2). The theory of the "hydraulic" mechanism suggests that blunt trauma to the eye increases the pressure of the orbital contents, which then causes a fracture of the thin and fragile parts of the orbital; the "buckling" mechanism explains that the orbital walls bend in response to impacts to the anterior rim, then fracture<sup>19-21</sup>. Most studies agree that both mechanisms are implicated in blowout fractures. One research group has suggested that the hydraulic mechanism tends to produce larger fractures of both the floor and medial wall while the buckling mechanism tends to produce smaller floor fractures<sup>22,23</sup>. Nagasao et al. showed that these two mechanisms may work synergistically, where fractures occur on wider areas of the orbital walls when the hydraulic and buckling mechanisms work simultaneously than when each of these mechanisms works separately<sup>24</sup>. A lesser-known theory is the "globe-to-wall" theory, where the globe is pushed posteriorly and directly fractures the medial wall and/or floor. One study reported that 44% of fractures fit the diameter of the globe<sup>25</sup>. However, cadaveric experimentation has not been able to reproduce these findings<sup>26</sup>.

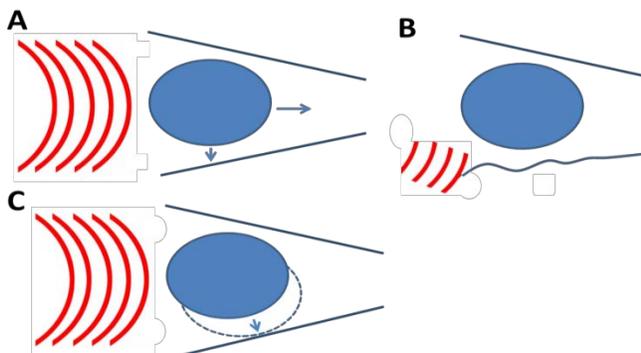


Figure 2. Schematic drawings of the three most widely accepted theories of the physical mechanism of blowout fractures.

2A shows the hydraulic mechanism where trauma to the globe increases pressure in the orbital cavity which produces a fracture. 2B shows the buckling theory where trauma directly to the inferior rim produces a buckling wave which fractures the floor. 2C shows the "globe-to-wall" theory where trauma to the globe pushes the globe against the orbital floor, thereby creating a fracture (adapted from Chapter 33 on [shortnotesinplasticsurgery.wordpress.com](http://shortnotesinplasticsurgery.wordpress.com)).

The medial wall (0.2 – 0.4 mm), also called lamina papyracea, is thinner than the orbital floor (0.5 – 1 mm)<sup>27</sup>. However, fractures of the orbital floor occur more frequently than medial wall fracture<sup>28</sup>. This is related to with the structure of the ethmoid. The classic theory of ethmoid cell development is a sinus cell concept. However, a new theory proposes that ethmoidal "conchae-like" endoturbinale elements originating from the ethmoid lateral wall are folded upon each other, creating pseudo sinus cells<sup>29</sup>. The theory is that this trabeculae structure of the ethmoid supports the medial wall. Patients with fewer ethmoid air cell septa and a larger medial wall area per septum are more likely to develop medial wall fractures than floor fractures<sup>30</sup>. Furthermore, evidence from cadaveric studies suggests that endoscopic ethmoidectomy makes the medial wall more likely to fracture than the floor<sup>31</sup>. There is no clear division between the medial and inferior orbital wall.

The EOMs can be identified on both CT and Magnetic Resonance Imaging (MRI) scans (Fig. 3). On CT scans, the muscles show slightly more intensity than the orbital fat. The EOMs are clearly delineated on MRI against the white orbital fat (T1 images). However, some areas may be difficult to distinguish from other tissues. For example, an exact determination of the insertion of the muscles is difficult due to the isointensity of tendon and scleral tissue on MRI<sup>32</sup>. The recti muscles are stabilized by the orbital connective tissue system<sup>14</sup>. The vertical muscles (superior and inferior recti) do not move sideways compared to the orbital bone in horizontal eye movements and neither do the horizontal muscles (lateral and medial recti) in vertical eye movements<sup>33</sup>.

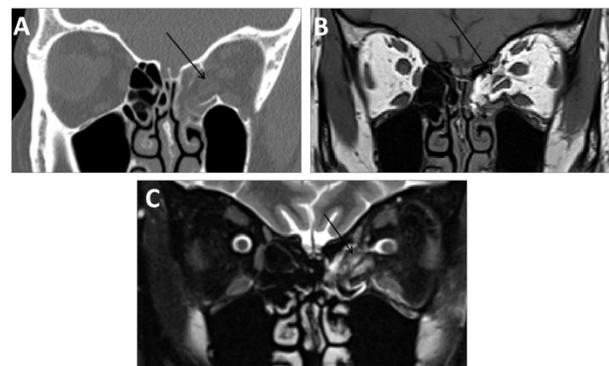


Figure 3. Coronal CT and MRI scans of a medial wall fracture of the left orbit. 3A shows CT scan. The bony walls are clearly delineated against soft tissue and air. 3B shows a T1 MRI scan. The white orbital fat and the darker EOMs are visible while the bone appears black. 3C shows a fat-suppressed T2 SPAIR MRI scan. Here, the fat is black and the muscles have comparatively more intensity. Black arrows point to the left medial rectus muscle in all three images.

### Clinical presentation

The hallmark signs of a blowout fracture are double vision (diplopia) and enophthalmos<sup>13</sup>. The diplopia may be in primary gaze

or only in secondary gaze. The diplopia may be caused by mechanical restriction due to a muscle entrapment (Fig. 4). Frequently, it is not directly the muscle itself that is entrapped, but instead fat tissue, which has connective tissue septa connected to the muscle sheath. Entrapment is considered an absolute indication for surgery and should be operated on as soon as possible to avoid muscle ischemia, fibrosis and permanent diplopia. Diplopia may also be caused by intraorbital edema restricting normal extraocular muscle movement.



Figure 4. Muscle entrapment in a patient with a blowout fracture. This patient has a left orbital floor fracture with entrapment of the left inferior rectus muscle. The patient is trying to look up with ocular motility restriction clearly visible on the left side.

A multidisciplinary approach to the patient is important. The clinical examination of the patient should comprise an evaluation by both an ophthalmologist and an otolaryngologist. The initial evaluation of a blowout fracture should include testing visual acuity, ocular motility and globe position. It is important not to overlook the possibility of a globe rupture, foreign bodies or an expanding orbital hematoma. Ocular motility may be evaluated by a visual field test, for example, Hess chart<sup>34</sup> and Hertel's ophthalmometry should be used to measure the globe position. A forced duction test can be performed to test for restriction of eye movement. The conjunctiva close to the limbus is gripped with forceps, and the globe is moved in multiple positions evaluating for any restriction in movement. The forced duction test is generally performed under general anesthesia since it is uncomfortable for a patient under local anesthesia.

The typical blowout fracture patient is a male aged 20 – 30 years who has been involved in a violent altercation<sup>35</sup>. Most studies have reported assault as the most common cause of blowout fractures followed by falls and traffic accidents; however, the incidence of traffic related accidents may differ between populations<sup>36</sup>.

#### Indications for surgery

The exact indications for surgery are varying and controversial. However, there is usually consensus about a few conditions, which requires immediate attention. Urgent intervention is indicated in muscle entrapment with the oculocardiac reflex (bradycardia, nausea, vomiting). This may be present in children in the so-called trapdoor fracture, where the bone bounces back in place and traps the muscle/fat thereby limiting ocular motility. Retrobulbar hemorrhage is a rapidly progressive sight-threatening condition, which also requires immediate intervention. An acute lateral canthotomy with cantholysis should be performed to relieve orbital pressure<sup>37</sup>.

There is no consensus concerning relative indications for surgery. Persistent diplopia two weeks after the trauma has been suggested as a criterion for surgery<sup>38</sup>. Several predictors of enophthalmos have been suggested such as criteria for surgery. Patients with fractures involving greater than 50% of the orbital

floor, or involving an area greater than 1 – 2 cm<sup>2</sup>, or herniated mass > 1.5 ml have been suggested as surgical candidates<sup>39-41</sup>.

#### Surgical management

The total number of blowout fractures in Denmark may be around 200 – 300 per year. Blowout fractures are managed by ten otorhinolaryngology or specialized hospital odontological departments throughout our country. The goal of surgery is to secure ocular motility and restore the orbital volume. Historically, three incisions have been used for orbital floor repair: transconjunctival, subciliary, and subtarsal. The transconjunctival incision is now used increasingly frequently, and can be performed either pre- or retroseptally. This approach has fewer complications than the other approaches<sup>42</sup>. Following the incision, the orbital rim is reached and a subperiosteal dissection is performed. Herniated fat is pulled back into the orbital cavity and an implant is placed over the bony defect. Damage to the infraorbital nerve should be avoided. Different implant materials have been used for blowout fracture surgery, for instance, autogenous bone and cartilage, porous polyethylene, polydioxanone (PDS), resorbable implants and titanium mesh. Although there may insufficient evidence to prefer one type of material from another, titanium mesh seems to be gaining popularity for orbital floor reconstruction (Fig. 5).

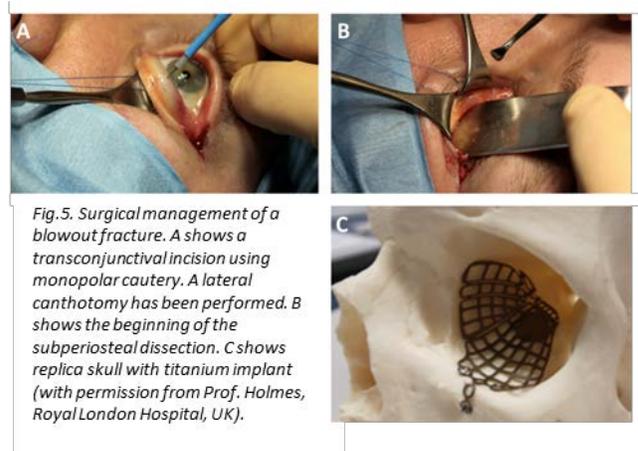


Fig.5. Surgical management of a blowout fracture. A shows a transconjunctival incision using monopolar cautery. A lateral canthotomy has been performed. B shows the beginning of the subperiosteal dissection. C shows replica skull with titanium implant (with permission from Prof. Holmes, Royal London Hospital, UK).

#### MEASUREMENTS OF THE ORBIT

In addition to the clinical examination, morphometric data of the orbit may help the surgeon both in deciding whether or not to operate and in selecting the surgical procedure<sup>43</sup>, and many different types of parameters can be extracted from the orbit. Image segmentation is the process of identifying and separating objects of interest from the rest of the image. It involves determining the correct borders of the region of interest as well as delineating the spatial extent of the structure. Regarding the orbit, this would correspond to deciding what constitutes the orbit and the actual task of marking the outlines of the orbit. The orbit is a complex 3D structure with four openings: the anterior opening, the superior and inferior orbital fissures and the optic canal. Differences in choice of borders of the orbit may make comparisons of studies difficult. Borders between tissue regions are difficult to delineate. In the case of the orbit, it can be air to bone or soft tissue to bone.

There are different techniques which may be utilized to measure the orbit. Most techniques are defined as manual, semi-automatic or automatic. Manually tracing the outlines of the region of interest may be time-consuming, but it is necessary for some structures. A different method is stereology, which uses

systematic random sampling to provide unbiased data<sup>44</sup>. Volumes are estimated by using a superimposed point-counting grid on sections of the region of interest. The first section through the region of interest is taken at a random start (hence the word “random” within the name) and the remaining sections are taken at regular sampling intervals (“systematic”) throughout the region of interest, until it has been completely sectioned. Automatic segmentation is fast and user-friendly and uses thresholding software, which can differentiate between pixel intensity of two tissues, for instance, white bone and black air on a CT scan. However, concerns have been raised about the accuracy of the thresholding components of the software programs<sup>45</sup>. Nevertheless, automatic methods seem to be best suited for the everyday clinical challenges in facial traumatology compared to the more time-consuming methods (manual and stereological methods).

## METHODS

### PAPER I:

A retrospective study of isolated fractures of the orbital floor and/or medial wall treated at our department between January 1, 2010 and December 31, 2013. Records of extra-ocular muscle function, eye displacement, visual acuity and mechanism of trauma were obtained from the medical notes. Diplopia was noted as double vision in primary gaze (diplopia involving primary gaze) or as an isolated secondary gaze diplopia.

### PAPER II:

CT scans were performed on 11 human cadavers. The volume and surface area of the orbital cavities were determined by using a stereological technique with a point and intersection counting method.

### PAPER III:

Blowout fracture patients were enrolled in a prospective controlled study and underwent an MRI scan within 72 hours after the trauma and again after 10 – 14 days. Measurements of the intraorbital contents were performed including volume, cross-sectional area and mean gray value (MGV) of extraocular muscles and fat tissue. A manual method was used for the measurements. Healthy volunteers without prior orbital disease were used as controls.

### PAPER IV:

The distances to the ethmoidal arteries were measured directly in 50 intact orbits. A Lynch incision was made between the medial canthus and the dorsum nasi. The periosteum lining the medial orbital wall was lifted carefully and the anterior and posterior ethmoidal arteries were found by blunt dissection along the frontolacrimal and the frontoethmoidal suture. The arteries were cut 5 mm lateral to the ethmoidal foramina. The intraorbital content and the lateral orbital wall were removed to give space for the measurements. A modified caliper was used for all measurements. Distances were measured from the posterior and anterior lacrimal crest, the intersection of the nasomaxillary and frontomaxillary suture, and from the nasion (intersection of the nasal bones and the frontal bone) to the ethmoidal foramina and the optic canal in the orbit.

Twenty-four other cadavers were CT scanned and distances were measured from above-mentioned anterior landmarks to the ethmoidal foramina and the optic canal in the orbit.

## RESULTS

### PAPER I:

A retrospective study of 100 consecutive patients with an isolated orbital fracture, where 60 had available follow-up data. Thirty-six patients had been managed surgically and 24 conservatively. The numbers of patients with diplopia and enophthalmos were reduced at the 3-month follow-up in both the group managed surgically and that managed conservatively. Twelve of the 36 patients managed surgically (33%) had residual peripheral diplopia 3 months after surgery. Seven of the 24 patients who were managed conservatively (29%) also had peripheral gaze diplopia 3 months after injury.

### PAPER II:

The orbits of 11 human cadavers were measured using a stereological sampling technique. The mean ( $\pm$ SD) total volume and total surface area of the orbital cavities were  $24.27 \pm 3.88 \text{ cm}^3$  and  $32.47 \pm 2.96 \text{ cm}^2$ , respectively. There was no significant difference in volume ( $p = 0.315$ ) or surface area ( $p = 0.566$ ) between the two orbital cavities.

### PAPER III:

Twenty-one patients with a blowout fracture were included. The volume and largest cross-sectional area of the extraocular muscle closest to the fracture was significantly larger compared to the same muscle on the normal side on both the first ( $p = 0.006$  and  $p = 0.026$ ) and second MRI scan ( $p = 0.010$  and  $p = 0.009$ ). MGv of the extraocular muscle closest to the fracture was significantly higher compared to the same muscle on the normal side on the first ( $p = 0.018$ ) but not the second coronal MRI scan ( $p = 0.273$ ). The volume of herniated orbital contents was significantly smaller on the second scan than on the first ( $p = 0.011$ ). No side differences in orbital measurements were found in the control group.

### PAPER IV:

Fifty intact orbits from 25 Caucasian cadavers were exenterated and examined directly. Additionally, high-resolution CT images of 48 orbits from 24 other Caucasian non-exenterated cadavers were examined. Distances were measured from four different anterior landmarks to the anterior ethmoidal foramen (AEF) and the posterior ethmoidal foramen (PEF) and the optic canal (OC). Ranges from the anterior landmarks to the ethmoidal arteries were, on average, 10 mm. Distances from the most anterior landmarks to the arteries were positively correlated with the length of the medial wall. Measurements of the distances from the posterior lacrimal crest to the ethmoidal arteries on CT images were feasible with a low intra- and interobserver variability.

## DISCUSSION

In our retrospective study (Paper I), a third of the patients treated for blowout fractures had persistent double vision 3 months post-trauma, irrespective of whether or not they had been managed surgically or conservatively treated. In addition, it was not directly readable in the patients' file which criteria had been used to select patients for surgery. We have not yet been able to set valid imaging criteria to be used for selecting patients with blowout fractures for surgery or not. According to the AO Foundation<sup>46</sup>, criteria for surgical treatment of an orbital floor fracture are:

- Significant internal orbital defects proven by imaging

- Disturbances of eye mobility that are the result of incarceration of ocular muscles
- Enophthalmos
- Exophthalmos secondary to blow-in fractures
- Hypophthalmos

These criteria are not based on high-evidence studies such as randomized controlled trials or systematic reviews thereof, but they reflect an agreed consensus based on studies of lower levels of evidence as well as expert opinion. No recommendations for a critical size of the defect are listed here other than “significant”. As mentioned, some criteria for defect size have been proposed (see above). However, there is currently no consensus on which criteria to use as indications for surgery in patients with blowout fractures. Furthermore, papers on criteria for surgery of facial fractures are typically published in journals with a relatively low impact factor. It is paradoxical that more focus has not been put on these cases given the impact of the orbital trauma has on the patients, who may potentially develop severe functional deficits and aesthetic deformities associated with reduced quality of life. Consequently, evidence-based clinical guidelines with defined indicators are warranted.

As a side note, we found that 14 of the 60 patients had not been examined by an ophthalmologist. Even though these were probably patients with minimal or moderate signs or symptoms, it nonetheless highlights a need for a more systematic approach to the initial examination of the patients.

The association between hospital procedure volume and clinical outcomes is well established<sup>47,48</sup>. In Denmark, there may be around 200 – 300 blowout fractures per year. Blowout fractures are managed by ten otorhinolaryngology or specialized hospital odontological departments throughout the country. This suggests that a centralization of blowout fracture surgery may help to maintain a sufficient patient load for orbital surgeons. Moreover, having otorhinolaryngologists, ophthalmologists and radiologists at the same hospital is essential for optimal surgical decisions offering the patient the best treatment.

Many studies on blowout fractures assume that the two orbits are equal in all morphometric measurements. The unfractured orbit has been used as a control in studies on surgical decision making as well as studies on orbital reconstruction<sup>49</sup>. However, the orbits may not be identical in regards to all morphometrics. We found no significant differences in volume or surface area of the left and right orbital cavities in 11 human cadavers using a stereological method (Paper II). The distances to the ethmoidal arteries were similar between sides in our direct measurements but differed in few of the CT measurements (Paper IV). No significant differences were found in volume, cross-sectional area and mean gray value of extraocular muscles as well as total fat volume between the left and right orbit on MRI scans of healthy participants (Paper III). These findings corroborate previous assumptions that the healthy side may be used as a control in studies on surgical decision making in blowout fractures. Accordingly, the non-traumatized side may be used as an anatomical reference in studies that focus on size of the defect compared to patient outcomes. Furthermore, the healthy orbit is often used as a template for reconstructing a fractured orbit. A new study has focused on the precision of different implants in reconstructing the fractured to the same size as the healthy orbit. Computer-designed patient-specific titanium implants were found to be more precise than both preformed standard implants and

patient specific implants formed over a 3D printed model of the healthy orbit<sup>49</sup>. However, patient outcomes 12 weeks post-surgery did not differ significantly in the three groups. This may reflect the fact that precision in orbital reconstruction is important but “extra precision” may not necessarily benefit the patient.

To the best of our knowledge, Paper III is the first study with longitudinal MRI scans of blowout fractures and the first to show dynamic changes in the intraorbital contents in the first post-traumatic days. Signs of edema in the intraorbital soft tissue in the initial post-traumatic days in patients with blowout fractures have been shown in some studies. One study found changes in the shape of the inferior rectus muscle in orbital floor fractures with a more round shape than the usual ellipsoid<sup>50</sup>. Data from our 21 patients with blowout fractures (Paper III) showed that the volume and largest cross-sectional area of the extraocular muscle closest to the fracture was significantly larger compared to the same muscle on the normal side on both the first and second MRI scans. MGVs of the extraocular muscle closest to the fracture were significantly higher compared to the same muscle on the normal side on the first but not the second coronal MRI scan. The volume of herniated orbital contents was significantly smaller on the second scan than the first. These findings indicate an initial intraorbital edema in the first post-traumatic days which shows signs of subsiding by days 10 – 14 post-trauma. It is likely that double vision is partly caused by EOM edema. The timing of surgery in blowout fractures is controversial. A systematic review concluded that current evidence is insufficient to support guidelines on the best timing for non-immediate orbital reconstruction<sup>51</sup>. However, another systematic review has shown a significantly increased risk of persistent diplopia in patients who were operated upon >14 days after the trauma<sup>52</sup>. We recommend a watchful waiting, i.e. a close follow-up period especially in the first 2 weeks in order to allow spontaneous remission of symptoms in patients and, at the same time, to be able offer the patient surgery when indicated.

The 24-12-6 mm rule of thumb determines distances from the anterior lacrimal crest to the ethmoidal arteries and the optic canal in the orbit. We questioned the applicability of this rule to all patients and investigated whether or not it is feasible to measure the distances on CT images. We found large interindividual differences and found that preoperative measurements on CT images are feasible and produce results with a low intra- and interobserver variability. Our findings support avoiding absolute rules such as the 24-12-6 mm rule and instead performing preoperative surgical planning on a CT scan. Operating without prior knowledge on the exact position of the arteries is possible, but could be compared with functional endoscopic sinus surgery without presurgical planning based on a CT scan. Using CT scans and measuring from the posterior lacrimal crest provides critical preoperative information for the surgeon which increases chances of a successful surgical outcome.

## CONCLUSIONS

This project studied clinical, radiological, anatomical and pathophysiological aspects of the orbital cavity. The studies were based on collaboration between five hospital/university departments (otorhinolaryngology, ophthalmology, radiology, anatomy and odontology). A multidisciplinary approach to blowout fractures is essential in order to obtain optimal patient outcomes. We wanted to assess the current treatment of patients diagnosed and treated for blowout fractures in our clinic. In our retrospective study

covering 60 patients, a third of the patients had persistent double vision 3 months post-trauma, irrespective of whether they had been managed surgically or conservatively. Clinical guidelines based on a higher level of evidence, e.g. prospective studies with defined indicators, are warranted.

A non-traumatized orbit may be used as an anatomical reference to the traumatized orbit only if the two orbital cavities originally were symmetrical. The left and right orbit and their contents were found to be symmetrical with regards to several morphometric parameters including total volume and surface area, volume of total orbital fat, volume of extraocular muscles and distances to the ethmoidal arteries.

Knowledge of the pathophysiology of the intraorbital contents in blowout fractures is a basis for our understanding of how diplopia and enophthalmos develop. In the first longitudinal MRI study of blowout fractures, we found on MRI scans that the intraorbital soft tissue showed signs of edema in the initial post-traumatic days, i.e. with larger volume, cross-sectional area and enhanced mean gray values of extraocular muscles and a subsiding volume of herniated mass. A watchful waiting and close follow-up period especially for the first 2 weeks post-trauma is recommended before deciding on surgical or conservative treatment.

Knowledge of the location of arteries in the orbital cavity is a prerequisite for safe orbital surgery. The 24-12-6 mm rule of thumb concerning distances from the anterior lacrimal crest to the ethmoidal arteries and the optic canal is not a mould that fits all since interindividual differences are significant. Measuring from the posterior lacrimal crest on a CT scan is feasible and produces results with a low intra- and interobserver variability.

## PERSPECTIVES

The management of blowout fractures is challenging. The total number of orbital fractures in Denmark may be around 200 – 300 per year. Blowout fractures are managed by ten otorhinolaryngology or specialized hospital odontological departments throughout our country. A further centralization of the management of blowout fractures could possibly enhance the treatment based on the low levels of fractures per department. Treating the patients in larger centers would also make multidisciplinary collaboration more straightforward. National and international guidelines, including plans for systematic follow-up regimes, should be established with inputs from all relevant specialties aiming to develop the best evidence-based treatment for the patients – and there seems space for this.

Imaging and cadaveric studies have provided an insight into the structural changes and the post-traumatic tissue dynamics of a blowout fracture. The volume of the herniated orbital tissue, the subsequent spontaneous reduction in this volume, and the spontaneous reduction in the post-traumatic edema can be readily observed. However, several questions regarding blowout fractures still remain unanswered. Specifically, if and when to operate on a blowout fracture are still questions that are dependent on many variables and not easily answered, although current knowledge is in favor of operation within 10 – 14 days. It is still not known what causes the double vision and we cannot pinpoint the patients who will develop enophthalmos. We have shown that MRI can detect the subtle changes with respect to volume shift and edema occurring in the post-trauma period. Future studies using real-time MRI of extraocular movements may also enable us, in addition to examining edema of affected orbital muscles, to correlate quantitatively the motion degree in

comparison with clinical testing in patients with diplopia<sup>53</sup>. Electromyography studies of the extraocular muscles may also be helpful in detecting whether a partial neurogenic paresis is present post-trauma.

The ethmoidal arteries course through the orbit and into the sinonasal area where iatrogenic damage of the arteries also may occur. Performing orbital or sinus surgery along with a delineating of the arteries on the CT and putative on MRI scans as a part of navigation or image guided surgery may further develop minimal invasive surgery CT aiming to reduce the treatment morbidity.

## SUMMARY

Isolated fractures of the orbital floor or medial wall are often referred to as blowout fractures (BOFs). Debilitating double vision and aesthetic deformity may affect the patients' quality of life and daily living skills, for instance, working or driving a car. The management of blowout fractures is, however, challenging, since not all fractures demand surgery. Some patients may have symptoms which subside, or may never develop symptoms. Due to a lack of evidence, there are still considerable differences in opinion on the criteria for surgery. The selection of patients for surgery is therefore crucial for optimal patient outcomes.

The aims of this PhD project were to elucidate and investigate various clinical aspects of blowout fractures and to examine the anatomy of the orbital cavity, which included studying the symmetry of the two orbits, the location of orbital arteries, and the pathophysiology of blowout fractures. Several clinical specialties and basic research fields study the orbital cavity. The studies in this PhD project are based on collaboration between the Departments of Otorhinolaryngology, Ophthalmology and Radiology at the Copenhagen University Hospital Rigshospitalet and the Departments of Odontology and Anatomy (Cellular and Molecular Medicine) at the University of Copenhagen.

We assessed the current treatment of blowout fractures at the Ear Nose and Throat (ENT) Department at our tertiary hospital in a retrospective study, and found that a third of the patients had persistent double vision 3 months post-trauma, irrespective of whether they had been managed surgically or conservatively (Paper I). We found that the left and right orbit are symmetrical with regards to various morphometrics of both the bony orbit and the intraorbital contents, e.g., volume, surface area and volume of fat and extraocular muscles, and distance to the ethmoidal arteries (Papers II, III and IV). This knowledge may be used in blowout fracture studies on surgical decision-making and orbital reconstruction and also in presurgical planning to avoid iatrogenic damage to the ethmoidal arteries in orbital surgery. In the first longitudinal MRI study of blowout fractures, dynamic post-traumatic changes in the intraorbital soft tissue were detected, i.e., to the best of our knowledge, for the first time indicative of an edema. We conclude that an edema subsides in the days following a blowout fracture and recommend a watchful waiting period before deciding on whether or not to operate (Paper III).

The 24-12-6 mm rule of thumb determines orbital distances from the anterior lacrimal crest to the ethmoidal arteries and the optic canal. We questioned the applicability of this rule to all patients and investigated whether or not it is feasible to measure the distances on Computed Tomography (CT) images. We found large inter-individual differences in the distances to the ethmoidal arteries and found that preoperative measurements on

CT images are feasible and produce results with a low intra- and inter-observer variability.

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