Orbital Blowout Fractures

Experimental Evidence for the Pure Hydraulic Theory

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Background: The mechanism of injury and the underlying biomechanics of orbital blowout fractures remain controversial. The “hydraulic” theory proposes that a generalized increased orbital content pressure results in direct compression and fracturing of the thin orbital bone.

Objective: To examine the pure hydraulic mechanism of injury by eliminating the factor of globe-to-wall contact and its possible contribution to fracture thresholds and patterns.

Materials and Methods: Five fresh human cadaver specimens were used for the study. In each cadaver head, 1 orbit was prepared to mimic the normal physiologic condition by increasing the hypotony of the cadaver globe to normal intraocular pressure (15-20 mm Hg) with intravitreous injection of isotonic sodium chloride solution (saline). The second orbit served as a “hydraulic control,” whereby the globe and orbital contents were exenterated and replaced by a saline-filled balloon at physiologic intraocular pressure. A 1-kg pendulum measuring 2.5 cm in diameter was used to strike the cadaver heads. Drop heights ranged from 0.2 m to 1.1 m (1960 mJ to 10780 mJ energy). Each head was struck twice, once to each orbit. Direct visualization, high-speed videography, and computed tomographic scans were used to determine injury patterns at various heights between the 2 orbits.

Results: A fracture threshold was found at a drop height of 0.3 m (2940 mJ). Fracture severity and displacement increased with incremental increases in drop height (energy). Fracture displacement, with herniation of orbital contents, was obtained at heights above 0.5 m (4900 mJ). Isolated orbital floor fractures were obtained at lower heights, with medial wall fractures occurring in conjunction with floor fractures at higher energies (≥6860 mJ). The globe intact side and balloon (hydraulic control) side showed nearly identical fracture patterns and levels of displacement at each drop height.

Conclusions: This study provides support for the “hydraulic” theory and evidence against the role of direct globe-to-wall contact in the pathogenesis of orbital blowout fractures. In addition, the orbital floor was found to have a lower threshold for fracture than the medial wall. Preliminary threshold values for fracture occurrence and soft tissue displacement were obtained.

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The mechanism of injury of orbital blowout fractures has long been an area of debate for otolaryngologists, ophthalmologists, and plastic surgeons. Sequelae such as diplopia, enophthalmos, hypophthalmos, and sensory disturbances in the distribution of the infraorbital nerve are well-recognized morbidities of orbital fractures.1,2 An elucidation of the underlying mechanisms of orbital fractures is not only of academic interest, but also of clinical importance in terms of prevention and treatment.

The 2 most accepted theories in the mechanism of orbital floor fractures fall into 2 categories: increased hydraulic pressure with direct compression force vs transmitted buckling force via the orbital rim.3,4 Recently, Erling et al5 resurrected an older theory on the etiology of orbital blowout fractures first espoused by an ophthalmologist in 1943.6 They proposed that the responsible mechanism of fracture is a direct globe-to-wall contact; that is, posterior movement of the globe, in response to an external force, results in a fracture upon direct contact with an orbital wall.

Of the 3 biomechanical theories, the “buckling mechanism” has been the most extensively studied.4,7 The “hydraulic” theory, as first advocated by Smith and Regan3 in 1957, proposed that a generalized increased orbital content pressure resulted in direct compression of the orbital floor, thereby causing fracturing of the thin bone. This classic cadaver study...
MATERIALS AND METHODS

Fresh, unfixed cadaver specimens were used for the study. Each of the 5 cadaver heads was prepared by having 1 orbit as the physiologic control (“globe intact”) and the other orbit replaced with a “balloon apparatus,” following removal of the entire soft tissue orbital contents. This intra-cadaver setup allowed comparison of the orbits at the same drop heights, thereby eliminating potential differences between cadaver specimens.

In the “globe intact” group, the orbital floor was examined endoscopically through an anterior maxillary wall antrostomy to ensure that the floor was intact prior to impact. The orbit was then prepared by injecting the globe with isotonic sodium chloride (saline). A Schiotz handheld tonometer was used to measure intraocular pressure. Approximately 4.5 mL of injected saline was necessary to achieve normal physiologic intraocular pressure (15-20 mm Hg).

The purpose of the “balloon apparatus” was to eliminate the globe as a possible factor in the pathogenesis of orbital fractures, yet still maintain the soft tissue content needed for the transmission of hydraulic forces. For this experimental group, the orbits were prepared by removing the globe and the orbital soft tissue contents. The orbital floor and medial walls were then closely inspected to ensure that they were intact and not disrupted by the exenteration process. The “balloon apparatus” consisted of 2 layered lambskin condoms with an 8 F Kao feeding tube tied into the open end of the condoms. The feeding tube allowed for the injection of 25 mL of saline, which correlated to the volume of the orbital contents. The balloon was placed into the orbit and the eyelid was loosely sutured over the balloon. The free end of the catheter was attached to a 30-mL syringe that was filled so that the top of the open column measured 15 cm above the center of the balloon, to approximate physiologic intraorbital pressure.

The cadaver heads were then impacted using a pendulum apparatus. The pendulum consisted of a 1-kg iron cylinder measuring 2.5 cm in diameter. The specimen was aligned with the pendulum to ensure that the globe alone would be impacted (Figure 1). High-speed videography was used to document that impact occurred directly on the orbital contents and not the orbital rims. Each cadaver head was struck twice, once to each orbit.

Following impact, in the “globe intact” group, the orbital contents were carefully removed leaving the periorbital intact to support the fractured orbital walls. The fracture patterns were then carefully painted with methylene blue and digital pictures were taken to document extent of injury (Figure 2). For the “balloon apparatus” group, the balloon was deflated and removed, and fracture patterns were documented as in the “globe intact” group. Computed tomographic scans were performed on 2 of the cadaver heads prior to orbital exenteration to document fracture patterns before manual manipulation of the orbital contents.

Drop heights were chosen initially to ensure occurrence of fracture, based upon previous studies. The drop heights were subsequently decreased until a fracture threshold was determined. Energy delivered by the pendulum was calculated using the following equation: \( U = mgh \), where \( U \) = energy (millijoules), \( m \) = mass (grams), \( g \) = gravitational acceleration (meters per second squared), and \( h \) = height (meters). Drop heights ranged from 1.1 m (10780 mJ) to 0.2 m (1960 mJ).

is often quoted as the definitive article purporting the “hydraulic” theory. Interestingly, this study reports only a single cadaver specimen and is flawed by questionable methodology and interpretation.

The role of direct globe-to-wall contact remains unclear, as no experimental studies have been conducted to validate or disprove this theory. The purpose of this study was to further examine the “hydraulic” mechanism of orbital wall fractures, and to elucidate the role of the globe in the pathogenesis of orbital blowout fractures.

RESULTS

Analysis of the high-speed videography revealed consistent impact of the pendulum to the orbital contents without impact to the orbital rim or other surrounding bones. The orbital rim was noted to be intact in all of the orbits. In general, fracture severity and bony displacement were greater with increasing drop heights. Orbital fractures were found with drop heights of 0.3 m or greater (2940 mJ). No orbital fractures occurred at 0.2 m (1960 mJ) (Table). Bony displacement, with herniation of orbital contents, was obtained only at heights above 0.5 m (4900 mJ). Fractures of the floor were obtained at lower heights, with medial wall fractures occurring in conjunction with the balloon.

The underlying biomechanics in the pathogenesis of orbital blowout fractures continues to be a controversial subject. The “hydraulic” theory, advocated by Smith and Regan1 in 1957, proposed that a generalized increased orbital content pressure resulted in direct compression of the orbital floor, thereby fracturing the thin orbital bone. In spite of their conclusions, the “hydraulic” theory was not substantiated by their study, and no quantitative measures of force needed to create the fractures were obtained.

Fujino4 later disputed this theory and proposed that a direct compression force or buckling force transmitted via the orbital rim was the causative factor for or-
bital floor fractures. This theory of bone conduction or “tsunami” mechanism of injury was first proposed by Le-Fort\(^1\) and Lagrange\(^8\) at the turn of the century. In his series of dried human cadaver experiments during the mid-1970s, Fujino\(^4\) convincingly demonstrated the occurrence of orbital floor fractures with direct blows to the orbital rim without fracturing the orbital rim itself. Phalen et al\(^7\) later corroborated Fujino’s findings by repeating his experiment on fresh cadaver heads, taking into account the soft tissue coverage of the orbital rim.

A more recent cadaver study by Waterhouse et al\(^9\) appeared to validate both the “hydraulic” and “buckling mechanism” theories. The study showed that each mechanism could independently produce orbital floor fractures via different biomechanics. In addition, they found that the fracture patterns differed between orbits struck on the orbital rim vs directly on the globe. The “hydraulic” mechanism produced larger fractures with involvement of the floor and medial wall, where herniation of orbital contents was frequent. The “buckling mechanism” produced smaller fractures involving the mid-medial floor, without significant orbital content herniation. However, the role of the globe in the pathogenesis of these fractures was not investigated.

Erling et al\(^5\) recently resurrected an older theory on the etiology of orbital fractures that was first described by Pfeiffer\(^6\) in 1943. They proposed that the responsible mechanism of fracture is direct globe-to-wall contact; that is, posterior movement of the globe, in response to an external force, results in a fracture upon direct contact with an orbital wall. In their analysis of computed tomographic scans of clinical cases of orbital blowout fractures, they found that the size of the orbital wall displacement often exactly fit the size of the globe. However, no corroborative experiments were conducted, and no such studies exist to support this theory, to date.

This study examined the role of the globe in the pathogenesis of orbital fractures by devising a mechanism to replace the orbital contents of 1 orbit with a “globeless” apparatus, and thereby effectively remove the globe as a factor in the fracture equation. Our findings demonstrate nearly identical fracture patterns between the “globe intact” and “balloon apparatus” groups at every drop height. Though these findings do not definitively rule out the possibility of the globe contributing to orbital fractures, this similar pattern of injury between the orbits suggests that direct globe-to-wall contact is an unlikely factor in the pathogenesis of orbital fractures. Furthermore, this study provides additional evidence for the “hydraulic” mechanism in its purest form.

Our data suggest that the threshold of energy needed to produce blowout fractures appears to be in the range of 1960 to 2940 mJ. Our study is the first to attempt to quantify the threshold using the fresh cadaver model for the “hydraulic” mechanism.\(^9,11,12\) Our threshold value is similar to that obtained by Green et al,\(^11\) the only in vivo study, human or nonhuman primate, to quantify the threshold for orbital fractures. In their study with Macaca fascicularis monkeys, they found that fractures of the orbital floor were consistently produced at and above 2080 mJ. Interestingly, in Phalen and colleagues’\(^7\) human cadaver study of the “buckling mechanism,” a similar threshold at 2500 mJ was found.

This threshold energy needed to cause orbital fractures is relatively low compared with the kinetic energies of missiles generated during sporting events. Racquet sports, in particular, can generate projectiles with enormous energies; a tennis ball (0.57 kg) hit at 100 mph will generate 11400 mJ, while a squash ball (0.24 kg) hit at 130 mph will generate 8100 mJ. Even the human fist, once set into motion, is capable of causing orbital fractures with energy measurements ranging from 900 to 3700 mJ.\(^11\)

Not surprisingly, the severity of the fracture, in terms of size, number of walls involved, and degree of orbital content herniation, correlated with increasing drop heights. Though larger number of drops need to be performed at each height before any definitive conclusions can be drawn, it was interesting to note that higher energies were needed to cause fractures of the medial wall. In addition, no medial wall fractures occurred without concomitant floor fractures. Though we are cautious in extrapolating our experimental findings to the clinical setting, our study suggests that in the absence of orbital rim or facial skeleton trauma (pure hydraulic mechanism), the orbital floor is more prone to fracture than the medial wall, and that isolated medial orbital wall frac-
tures cannot occur without trauma to the surrounding bony framework (eg, orbital rim and nasal bone).

In the clinical realm, orbital fractures may occur by way of the "buckling" or "hydraulic" mechanism, with a combination of the 2 mechanisms being the most likely scenario. A potential future study examining fracture patterns and threshold values with combined blows to the orbital rim (medial, inferior, superior, and lateral) and to the orbital soft tissue would allow for investigation into the additive effects of both mechanisms of injury.

The shortcomings of this study include the small number of specimens and the cadaver model itself. Larger numbers of drops are needed at each height to apply statistical analyses and thereby provide more powerful data. In addition, the age of the cadavers is well above the average of the population that usually sustains these injuries. However, previous studies have demonstrated that age is not thought to have a significant effect on facial bone strength.13

In conclusion, this study provides validation of the pure "hydraulic" theory and evidence against the role of direct globe-to-wall contact in the pathogenesis of orbital blowout fractures. In addition, the orbital floor was found to have a lower threshold for fracture than the medial wall, and preliminary threshold energy values for fracture occurrence and bony displacement were obtained.

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REFERENCES


![Figure 3. Coronal computed tomographic scan of orbits demonstrating similar floor and medial wall fractures between the "globe intact" orbit (A) and the "balloon apparatus" orbit (B) at a drop height of 0.7 m.](image)

<table>
<thead>
<tr>
<th>Drop Height, m</th>
<th>Energy, mJ</th>
<th>Globe Intact vs Balloon</th>
<th>Floor</th>
<th>Medial Wall</th>
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<tbody>
<tr>
<td>1.1</td>
<td>10 780</td>
<td>Globe intact</td>
<td>2.8 x 2.3</td>
<td>1.4 x 1.2</td>
</tr>
<tr>
<td>1.1</td>
<td>10 780</td>
<td>Balloon</td>
<td>3.0 x 2.5</td>
<td>1.4 x 1.0</td>
</tr>
<tr>
<td>0.7</td>
<td>6860</td>
<td>Globe intact</td>
<td>3.0 x 2.0</td>
<td>2.0 x 1.5</td>
</tr>
<tr>
<td>0.7</td>
<td>6860</td>
<td>Balloon</td>
<td>3.0 x 2.5</td>
<td>2.0 x 2.0</td>
</tr>
<tr>
<td>0.5</td>
<td>4900</td>
<td>Globe intact</td>
<td>3.0 x 2.0*</td>
<td>2.0 x 2.0*</td>
</tr>
<tr>
<td>0.5</td>
<td>4900</td>
<td>Balloon</td>
<td>3.0 x 2.0*</td>
<td>NF</td>
</tr>
<tr>
<td>0.3</td>
<td>2940</td>
<td>Globe intact</td>
<td>3.0 x 2.0*</td>
<td>NF</td>
</tr>
<tr>
<td>0.3</td>
<td>2940</td>
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<td>3.0 x 2.0*</td>
<td>NF</td>
</tr>
<tr>
<td>0.2</td>
<td>1960</td>
<td>Globe intact</td>
<td>NF†</td>
<td>NF</td>
</tr>
<tr>
<td>0.2</td>
<td>1960</td>
<td>Balloon</td>
<td>NF†</td>
<td>NF</td>
</tr>
</tbody>
</table>

*Non-displaced fracture.
†NF indicates no fracture.