学位論文

Frontal Bone Fracture Patterns Suggesting Involvement of Optic Canal Damage

香川大学大学院医学系研究科
医学専攻

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ORIGINAL ARTICLE

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Purpose: Fracture of the frontal bone can be accompanied by damage to the optic canal. The present study uses finite element analysis to identify fracture patterns, suggesting the involvement of the optic canal.
Methods: Ten finite-element skull models were generated from computer tomography data of 10 persons. Then, dynamic analyses simulating collision of a 2-cm-radius brass ball to 6 regions on the frontal bone in the 10 models were performed. Fracture patterns presented by the frontal bone in the 60 experiments were observed, and all those involving the optic canal were selected. Commonalities of the selected fracture patterns were identified.
Results: Fracture of the optic canal was observed in 9 of the 60 patients. In all 9 patients, fracture existed on the anterior and posterior walls of the frontal sinus and on the superior orbital wall.
Conclusion: When the anterior and posterior walls of the frontal sinus and the superior orbital wall are all broken, the optic canal is highly likely to be involved in the damage. When this pattern is observed in emergency examination, preventive decompression of the optic nerve should be considered to avoid potential occurrence of blindness.

Key Words: Blindness, finite element analysis, fracture, frontal bone, optic canal, orbit, simulation

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When the frontal region is strongly struck, the frontal bone can fracture.[1–5] The anatomical structure of the frontal bone presents inhomogeneity according to location.[6] Some parts of the frontal bone are thick, and others are thin. Some parts are adjacent to the frontal sinus, and others are not. Because of this structural unevenness, the frontal bone presents various fracture patterns, depending on which part is struck.

Among various fracture patterns, those involving the optic canal need to be treated with great care,[7] because fracture of the optic canal can cause edema of the optic nerve and subsequent blindness. The present study, using simulation with computer models, aims to identify the patterns of frontal bone fracture wherein the involvement of the optic canal should be suspected.

METHODS

Model Production

Computer tomography (CT) data of the skulls of 10 males (mean ± SD: 37.5 ± 6.7 years) were collected. The 10 patients had been randomly selected from those who received CT examination of the brain at Kagawa University Hospital for the screening of brain injury after trauma. None of the 10 patients had congenital anomaly of the skull. The usage of their data for the present study was agreed to by the patients, and the study design throughout this study was approved by the institutional review board of Kagawa University.

The CT data in DICOM (Digital Imaging and Communications in Medicine) files were transferred to preprocessor software (Scan IP; Simpleware Ltd, Exeter, UK), where the data were transformed to Standard Triangulated Language files, forming 3-dimensional simulation models of the 10 skulls. The models were divided into 1,450,000 to 1,890,000 tetrahedrally shaped 10-node elements. Appropriate specific density and Young's modulus were assigned to each element. Specific density was calculated by translating Housefield's gray scale[8]; Young's modulus was calculated based on the equation of Kopperdahl ($E = -34.7 + 3230$ QCT), where E and QCT mean Young's modulus (in megapascals) and CT density (in grams per milliliter), respectively.[9] Thus, 10 models reflecting the accurate shapes and material properties of the original 10 skulls were produced.

Dynamic Simulation of Impact Application

With each of the 10 models, a simulation experiment was conducted in which the frontal bone was struck with a 2-cm-radius brass sphere. We defined 6 round regions on the frontal area of each

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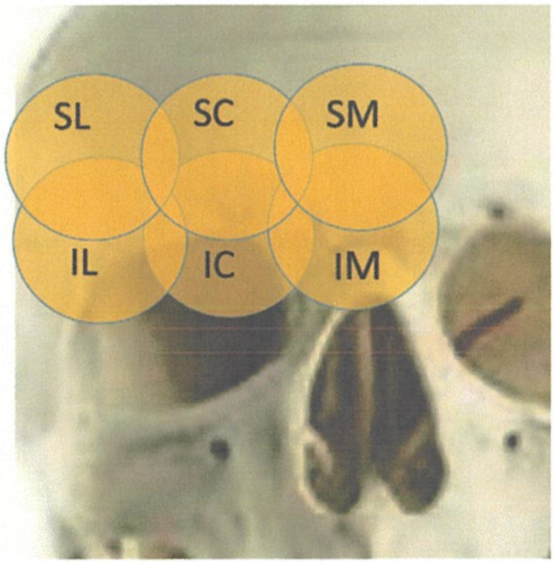

FIGURE 1. For each of the 10 finite-element skull models, 6 regions were defined on the forehead. SL, superior-lateral region; SC, superior-central region; SM, superior-medial region; IL, inferior-lateral region; IC, inferior-central region; IM, inferior-medial region.

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model: the superior-medial (SM) region, superior-central (SC) region, superior-lateral (SL) region, inferior-medial (IM) region, inferior-central (IC) region, and inferior-lateral (IL) region. The diameter of these 6 regions was defined to be 2 cm, so that the sphere could precisely strike each. These regions are demonstrated in Figure 1.

In a previous study, Waterhouse struck the eyes of cadavers by dropping a brass weight at the velocity of 6 m/s to produce blowout fractures.[10] The impact energy of this experimental condition is 7.4 joules. To produce fractures that could involve not only the orbital wall but also the optic canal, more intense energy must be applied. Hence, in the present study, we arranged the speed of the brass

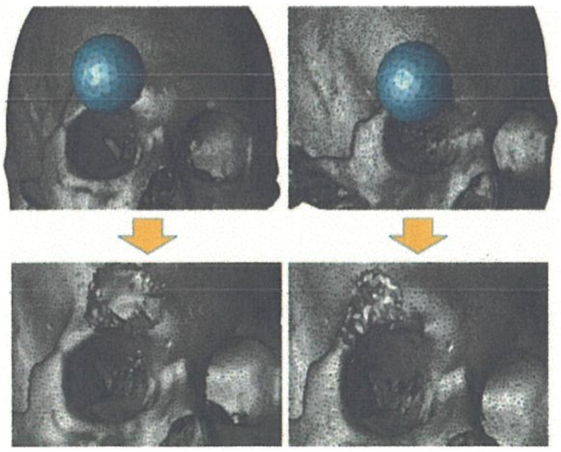

FIGURE 2. Dynamic simulation of impacting the forehead was conducted. The left and right figure pair demonstrates the impact on the superior-central and superior-lateral regions, respectively.

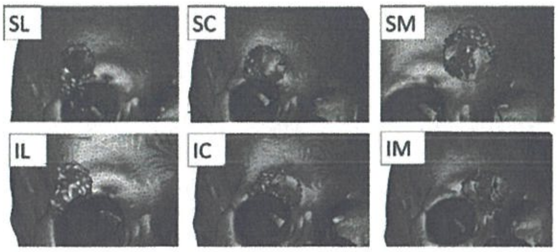

FIGURE 3. Examples of resultant fractures in macro view. The acronym on each picture indicates the impacted region. SL, superior-lateral region; SC, superior-central region; SM, superior-medial region; IL, inferior-lateral region; IC, inferior-central region; IM, inferior-medial region.

sphere to produce twice the energy of Waterhouse's experiment. The yield threshold of the bone was assumed to be 150 megapascals.[8,11] With these experimental conditions, we impacted the frontal bone, and calculated resultant fracture patterns with postprocessor software (Livermore Software Technology Corporation, Livermore, CA). Examples of impact application are demonstrated in Figure 2.

Evaluation of Fracture Pattern

The above-stated simulation, striking the 6 regions of each model, produced 6 resultant fractures as shown in Figure 3 (macro view) and Figure 4 (micro view). Since 6 results were obtained for each of the 10 skull models, 60 fracture patients in total were collected. Among the 60 patients, the patients where the optic canal was involved in fracture were identified. For these cases, evaluation was performed regarding the following 3 items.

Region-wise Frequency

Each model was struck at the 6 regions (Fig. 1). For each of the 6 regions, the frequency of presentation of optic-canal fracture was calculated.

Frequencies of Related Position Injury

The frequencies in which fracture involved the nasal bone, medial orbital wall, inferior orbital wall, lateral orbital wall, superior orbital wall, anterior and posterior walls of the frontal sinus, and zygoma were evaluated.

Time-Related Development of Fracture

The LS-DYNA solver allows us to observe the time-related progress of fracture. By using this function, how fracture initiated at the frontal bone came to involve the optic canal was observed.

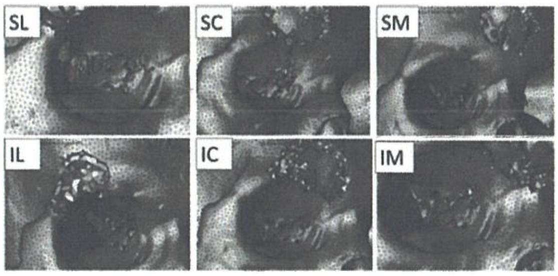

FIGURE 4. Examples of resultant fractures in orbit-focus views. The acronym on each picture indicates the impacted region. SL, superior-lateral region; SC, superior-central region; SM, superior-medial region; IL, inferior-lateral region; IC, inferior-central region; IM, inferior-medial region.

TABLE 1. Region-wise Frequency of Optic Canal Damage

Impacted Region	Frequency of Optic Canal Involvement
Superior lateral	0
Superior central	7
Superior medial	2
Inferior lateral	0
Inferior central	0
Inferior medial	0

TABLE 2. Involvement of Surrounding Structures in Optic Canal Damage Patients

Regions	Frequency of Optic Canal Fracture
Nasal bone	5
Orbital walls	
Superior wall	9
Medial wall	7
Inferior wall	0
Lateral wall	0
Frontal sinus	
Anterior wall	9
Posterior wall	9
Zygoma	0

RESULTS

Frequency of Optic Canal Involvement

In the 60 patients, fracture of the optic canal occurred in 9 patients.

Region-wise Frequency of Optic Canal Fracture

In the 9 patients with optic canal fracture, the fracture occurred in 7 patients after IC region impact and in 2 patients after SM region impact. Region-wise frequencies are shown in Table 1.

Frequencies of Fractures for Related Positions

Frequencies of fractures for the regions on and around the frontal bone are shown in Table 2. All 9 patients involving the optic canal had fractures on the superior orbital wall and the anterior and posterior walls of the frontal sinus.

Progress of Optic Canal Involvement

In all 9 patients with optic canal involvement, fracture progressed with the same pattern. First, the frontal wall of the frontal sinus broke; then the posterior wall broke; next, the superior orbital wall broke; eventually, fracture reached the optic canal. Time-course fracture development in a patient is shown in Figure 5.

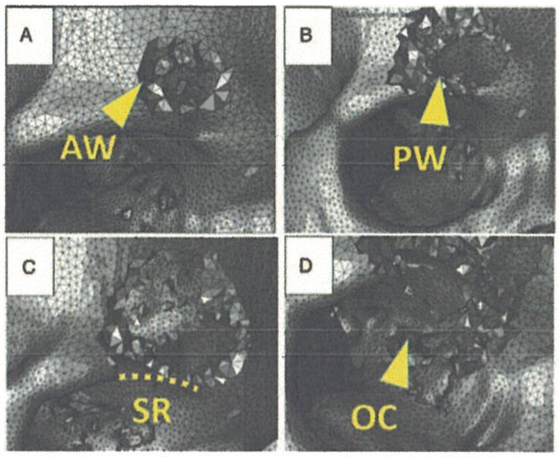

FIGURE 5. Representative pattern of fracture progress. (A) Fracture first occurs on the anterior wall of the frontal sinus (AW). (B) Then the posterior wall of the frontal sinus (PW) breaks. (C) The superior rim of the orbit (SR) breaks. (D) Fracture finally involves the optic canal (OC).

DISCUSSION

The frontal bone breaks when the forehead is strongly impacted. When the intensity of the impact exceeds a certain degree, the fracture is not localized in the frontal bone and extends to surrounding structures, including the cranial base, optic canal, and orbital walls.[1] Damage to these structures can cause liquorrhea,[12] blindness,[13] and diplopia,[14] respectively. Among these complications, blindness in particular seriously impairs patients' quality of life. Blindness is caused when injury of the optic canal results in subsequent edema of the optic nerve.

Habal and Maniscalco conducted a minute anatomical study regarding the structure of the optic nerve and classified it into 5 parts: the chiasmatic part, the intracranial part, the inter-canalicular part, the inter-orbital part, and the interocular part.[15] Habal and Maniscalco showed that the optic nerve lies adjacent to the sphenoid plate at the intracranial part, and to the optic canal at the inter-canalicular part. Demonstrating that the optic nerve is tightly surrounded by a bone wall at the inter-canalicular part, Maniscalco and Habal state that the optic canal can be injured in the event of trauma to the front-orbital region, referring to the potential necessity of decompression of the nerve.[16]

Hence, in examining trauma of the forehead, it is necessary to diagnose whether or not the optic canal is injured. Believing that identification of fracture patterns wherein injury of the optic canal is likely to occur is useful to making more precise diagnoses, we have undertaken the present study.

Finite-element simulation was used in the present study. Finite-element simulation is an established technique for medical research, and is used to clarify the biomechanical behaviors of such organs as facial bones,[17] thoraces,[18] and skin.[19] We employed finite-element simulation in the present study, because it guarantees accuracy of experimental conditions. In most previous studies regarding the mechanisms of facial bone fracture, actual human skulls were impacted, and resultant fracture patterns were observed.[20–22] With such methods, reproducibility and accuracy of the experimental conditions cannot be guaranteed because of instability of the conditions of impact application. In addition, ethically speaking, damaging actual human skulls is unacceptable in the 21st century. Finite-element simulation is advantageous from these standpoints, because it not only guarantees accuracy of experimental conditions but also has few ethical problems.

Human skulls vary in shape and hardness. Because of individual differences, a finding with 1 skull is not necessarily true for others. To avoid this problem and increase the generality of the findings, we performed the same set of experiments (brass-sphere impacting on 6 regions) with 10 skull models. Evaluation with 10 models improves the reliability of the findings.

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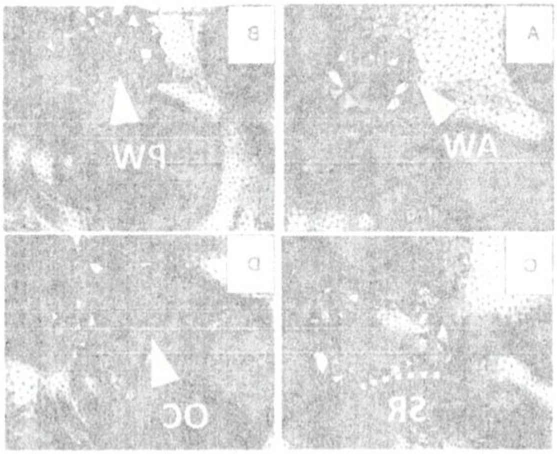

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Besides the accuracy of the experimental conditions, another methodologic advantage of finite-element simulation is that it enables observation of the progress of the fracture. In previous studies on actual human skulls, only the final condition of the fracture was observable; the process by which the fracture advances was unobservable due to the brevity of the time of impact application. On the contrary, with finite-element simulation, the progress of fracture can be observed at any moment (Fig. 5), by halting calculation. This function enables observation of how fracture initiated at the frontal bone advances to surrounding structures.

In all 9 patients where the optic canal was damaged, fracture first occurred at the frontal sinus, progressing to the upper orbital wall, and eventually breaking the optic canal (Fig. 6). This pattern, where the fracture continuously progresses from the directly impacted site to the opposite side, may appear a matter of course and unworthy of discussion. However, this pattern is not necessarily the case with other fractures. For instance, when the region around the infraorbital foramen is impacted, the directly impacted site and the inferior orbital wall may fracture. However, the inferior orbital rim, the structure between the 2 sites, often remains unbroken. This characteristic fracture pattern is given the special name "blowout fracture." Before performing this study, we had expected a similar phenomenon might occur with frontal bone fractures, presenting discontinuity between fractures at the frontal sinus and the optic canal, without the destruction of the upper orbital wall. However, such an enclave-like fracture pattern occurred in none of the 9 patients. In all patients where the optic canal was damaged, fracture occurred presenting a continuously progressive pattern.

In all 9 patients showing damage of the optic canal, fracture involved the anterior/posterior walls of the frontal sinus and the upper orbital wall. Inductive evaluation of this finding allows us to propose a diagnostic protocol: "When the anterior/posterior walls of the frontal sinus and the upper orbital wall are broken, the optic canal is highly likely to be involved in the damage, so injury should be suspected." This diagnostic protocol is useful in screening for optic canal injury at emergency rooms.

When the optic canal is injured, decompression of the optic nerve should be performed as soon as possible to prevent edema of the optic nerve and subsequent blindness. To perform this early stage prevention, damage to the optic canal must be screened for immediately after injury. However, identification of optic canal damage in an emergency room is often challenging for the following 2 reasons. First, the patient is often unconscious, so physicians cannot examine the patient's visual function. Second, the fracture of the optic canal is often too subtle, presenting only small slits, to be found in low resolution computer-tomographic images. Hence, in early stage screening, the fracture can go undetected.

The given diagnostic protocol works to reduce such misjudgment. When evident fracture is observed in the previously stated 3 structures (the anterior and posterior walls of the frontal sinus, and the upper orbital wall), the optic canal is likely to be damaged too, even if the damage is not evident. In such situations, the optic canal should be re-examined with computer tomography at a higher resolution, and double checked by a team of physicians. By taking such care, the occurrence of blindness can be prevented.

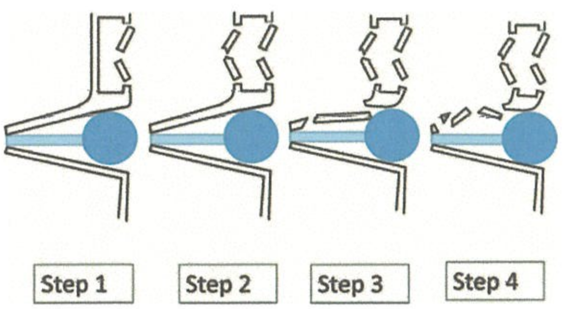

FIGURE 6. Schematic demonstration of fracture progress pattern.

The present study focused on mechanisms of frontal bone fracture. However, besides the frontal bone, fracture also occurs frequently on other facial bones, such as the zygoma, upper jaw, and nasal bone. We plan to extend our study to include these bones to clarify diagnostic protocols regarding these bones. We believe accumulation of such diagnostic protocols will greatly contribute to the accuracy of diagnosis of facial bone fractures.

Furthermore, recent advancement of microscopic and endoscopic surgical techniques enables surgeons to access the tissues around the optic canal and the cavernous sinus more accurately and effectively than in the past.[23,24] Accordingly, the necessity of evaluating damage to these structures in traumatic situations is increasing. In the present study, the damage to the optic canal was observed at the macro level. However, since the optic canal is a subtle anatomical structure, minor damage, even on scales <1 mm, can cause edema of the optic nerve and impair it. Hence, we plan to expand our studies to elucidate micro-level damage of the optic canal in traumatic situations in our future studies.

CONCLUSION

By using finite-element simulation, the present study analyzed various fracture patterns of the frontal bone. In 60 patients with dynamic simulation with 10 skull models, the optic canal was injured in 9 patients. All the 9 patients had fracture of the anterior and posterior walls of the frontal sinus and of the upper orbital wall in common. Inductive reference of this finding suggests a diagnostic protocol: "When the anterior and posterior walls of the frontal sinus and the upper orbital wall are broken, fracture of the optic canal should be suspected." Clinical application of this protocol in emergency diagnosis facilitates accurate screening of optic canal damage, and contributes to prevention of possible blindness.

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