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学位論文

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Separation patterns of orbital wall and risk of optic canal injury in Le Fort 3 osteotomy

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ABSTRACT

Purpose: The authors hypothesized that the risks of optic canal injury in down-fracturing after Le Fort 3 osteotomy vary depending on the separation patterns of the orbital walls. This study verifies this hypothesis using biomechanical simulation.

Methods: Ten finite-element skull models were produced using computer tomography data from ten persons. These models were modified to simulate Le Fort 3 osteotomy models by removing junctions between the neurocranium and facial cranium. The separation of the orbital wall was performed in four differing ways. In Type 1, all walls were completely separated. In Type 2, only the lateral wall was separated. In Type 3, the inferior wall was left unseparated. In Type 4, the lateral wall was left unseparated. Biomechanical simulation of down-fracturing was performed on the resulting 40 models. By observing irregular fractures occurring inside the orbit, the rate of optic canal involvement was evaluated for each of the four orbital-wall separation patterns.

Results: The rates of optic canal involvement were: Type 1 (0/10), Type 2 (0/10), Type 3 (0/10), and Type 4 (4/10).

Conclusion: When the lateral wall is incompletely separated in Le Fort 3 osteotomy, irregular fracture can develop inside the orbit and involve the optic canal during the down-fracturing process. Hence, the lateral orbital wall should be completely separated to avoid potential blindness due to optic canal injury.

1. Introduction

Le Fort 3 osteotomy is a surgical procedure used to correct midface hypoplasia in Crouzon, Apert, and Pfeiffer syndromes (Tessier, 1967; McCarthy et al., 1992; Cohen et al., 1995). Although Le Fort 3 osteotomy is a useful surgical technique, it can cause such complications as subarachnoid hemorrhage (Matsumoto et al., 2003), carotid-cavernous fistula (Uchida et al., 2006; Vyas et al., 2007), and blindness (Alonso et al., 2008; Hikosaka et al., 2008). This paper focuses on blindness. When down-fracturing is performed after osteotomy, irregular fracture can develop inside the orbit and involve the optic canal, resulting in blindness. We hypothesize that the risk of such optic canal injury varies depending on how the orbital walls are separated. This study elucidates whether or not the risks of optic canal injury vary depending on the patterns of orbital wall separation.

2. Materials and methods

This study — designed in keeping with the Helsinki Declaration — was approved by the institutional review board of Kagawa University.

2.1. Production of skull models

Among the male patients who visited Kagawa University Hospital and received computed tomography (CT) examination of the brain in the previous three years, ten male patients (mean age (years) 26.7 ± 10.5 SD) were randomly selected, and their CT data

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used for this study. The CT examinations were originally performed to detect suspected brain injury, and were therefore not carried out for the purposes of this study. Following the CT examinations, patient consent had been obtained for possible usage of the data for scientific studies. The CT data were transferred to a workstation (Dell Precision, Dell Co. TX, USA), where they were transformed into three-dimensional computer-aided-design (CAD) models using graphic converter software (+CAD Module, Simpleware Ltd. Exeter, UK). These CAD models were further transformed into finite-element models consisting of 124,000 to 178,000 10-node-tetrahedral elements with preprocessor software (Scan IP, Simpleware Ltd. Exeter, UK). The Young's modulus and specific gravity for each element were calculated and assigned according to local CT density (Bessho et al., 2007). Poisson's ratio was set as 0.326 (Nagasao et al., 2006).

2.2. Modification to Le Fort 3 osteotomy models

For each of the ten finite-element skull models produced with the above-stated method, simulation surgery of Le Fort 3 osteotomy was performed. Assuming that the neurocranium and the facial cranium were separated at the pterygomaxillary junction, nasal septum, nasal radix, and zygomatic arch, the elements at these sites were removed (Fig. 1). The orbital walls were separated into the following four patterns (Fig. 2):

Type 1 The lateral, inferior, and medial walls were separated.
Type 2 The lateral wall was separated; the medial and inferior walls were unseparated.
Type 3 The medial and lateral walls were separated; the inferior wall was unseparated.
Type 4 The medial and inferior walls were separated; the lateral wall was unseparated.

2.3. Dynamic simulation of down-fracturing

Dynamic simulation of down-fracturing was performed on the 40 Le Fort 3 osteotomy models. The region around the foramen magnum was fixed by assigning zero displacement to all the nodes of the elements belonging to this region. Simulating the effect of Rowe's maxillary down-fracturing forceps, 98 N (equivalent to 10-kg loading) forces were applied to bilateral nasal floors in the inferior direction. Dynamic events occurring in response to this load application were evaluated by performing calculations with LS-DYNA (Livermore Software Technology Corporation, Livermore, CA, USA). It was assumed that the bone breaks when its strain reaches 0.0004 (Nagasao et al., 2006). As the result of this load application, the neurocranium and facial cranium were separated at their junctions (Fig. 3).

2.4. Evaluation of risks of injury to optic canal

Some models developed irregular fracture inside the orbit (Fig. 4). For each of the four orbit-separation types, frequency of the involvement of the optic canal in irregular fractures was evaluated (Fig. 4).

3. Results

The conditions of the orbital walls of the ten models after down-fracture for Type 1 are shown in Fig. 5. Similarly, the post-down-fracture conditions for Type 2, Type 3, and Type 4 are shown in Fig. 6, Fig. 7, and Fig. 8, respectively. The frequencies of

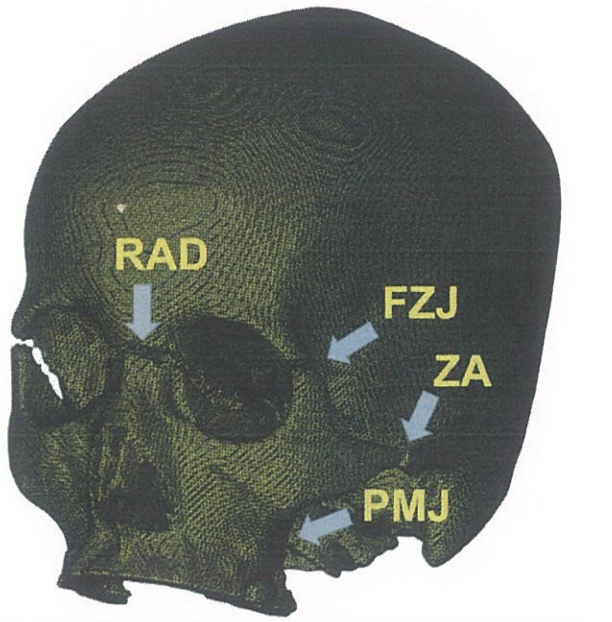

Fig. 1. With each of the ten skull models, the facial cranium was separated from the neurocranium at the radix of the nose (RAD), front–zygomatic junction (FZJ), zygomatic arch (ZA), and pterygomaxillary junction (PMJ), simulating Le Fort 3 osteotomy. Separation of the orbital wall was performed in four patterns (see Fig. 2).

optic canal fracture for the four separation types are shown in Table 1.

For each of the Type 1, Type 2, and Type 3 groups, no cases presented damage of the optic canal. In the Type 4 group, four out of the ten cases presented damage to the optic canal.

4. Discussion

Le Fort 3 osteotomy is an effective surgical procedure that enables correction of both midface hypoplasia and malocclusion. It divides the neurocranium and the facial cranium at their junctions to mobilize the facial cranium. Since the neurocranium and the facial cranium are firmly combined in the normal condition, forced separation of them can cause irregular fractures around their junctions. Serious complications can occur when such irregular fractures involve important anatomical structures. Anatomically, the neurocranium and facial cranium are connected at the zygomatic arch, pterygoid process, maxillary tuberosity, lateral orbital wall, frontal process of the zygoma, inferior orbital wall, medial orbital wall, and nasal radix. When down-fracturing is performed after the complete separation of the two crania at all these junctions, irregular fracture should not happen. However, some of these junctions exist at anatomically deep positions, or close to blood vessels. Hence, in reality, it is a challenge to perform separation at all the junctions. Therefore, it is necessary to establish which of the above-stated sites must be divided, and which can be left undivided. The authors performed this study to address this clinical question.

Many studies of Le Fort 1 osteotomy have been conducted in the past for the purpose of increasing the safety of the procedure. Renick and Symington evaluated the CT data of 12 patients who had undergone Le Fort 1 osteotomy and reported that pterygoid fracture can occur at certain percentages (low-level fractures 37.5%; high-level fractures 25%) (Renick and Symington, 1991). Lanigan and Guest investigated the relationship between methods of

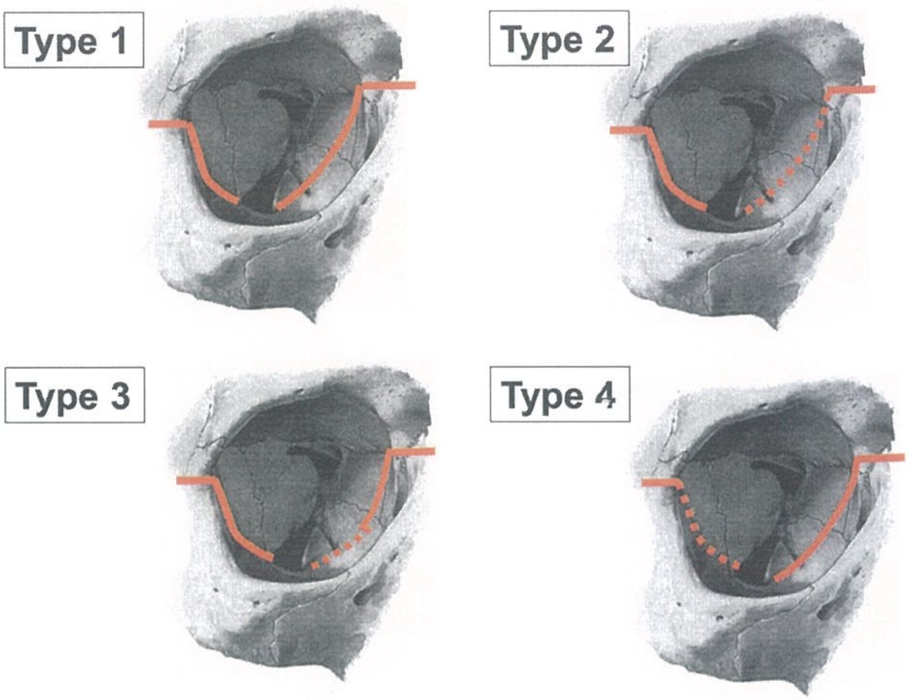

Fig. 2. The orbital wall was separated in four ways. In Type 1, the medial, inferior, and lateral walls were all separated. In Type 2, the medial and inferior walls were unseparated. In Type 3, the inferior wall was unseparated. In Type 4, the lateral wall was unseparated.

pterygomaxillary dysjunction and likelihood of irregular fracture, performing experimental surgery on 50 fresh cadavers. They demonstrated that use of a Stryker micro-oscillating saw is effective in avoiding devastating complications (Lanigan and Guest, 1993). Hoffman and Islam studied variation in the anatomical relationships between the maxillary tuberosity, the pyramidal process of the palatine bone, and the pterygoid plate. They reported that down-fracturing can cause damage to the pterygoid plate in some cases. Based on these findings, Hoffman and Islam stress the importance of preoperative evaluation of the anatomical features of the above-stated structures (Hoffman et al., 2008).

In contrast, few reports have studied the avoidance of complications in Le Fort 3 osteotomy. Herford — after measuring the tensions that occurred in experimental down-fracturing of 16 cadavers — demonstrated that tensions can increase in cases where incomplete osteotomy is conducted (Herford et al., 2000). Based on this finding, Herford concluded that complete osteotomy with pterygomaxillary dysjunction is effective in avoiding serious complications. Akita et al. — also focusing on pterygomaxillary dysjunction — elucidated osteotomy methods that can minimize the risk of complications in down-fracturing (Akita et al., 2013). They performed experimental surgery on 30 cadavers, where down-fracturing was performed after pterygomaxillary dysjunction in six different ways. They then examined the skulls with CT and evaluated the rates of irregular fracture. Based on the findings, Akita et al. reported that when pterygomaxillary dysjunction is conducted incorrectly, irregular fractures can develop at the skull base or pterygoid plate, and subsequent complications can occur.

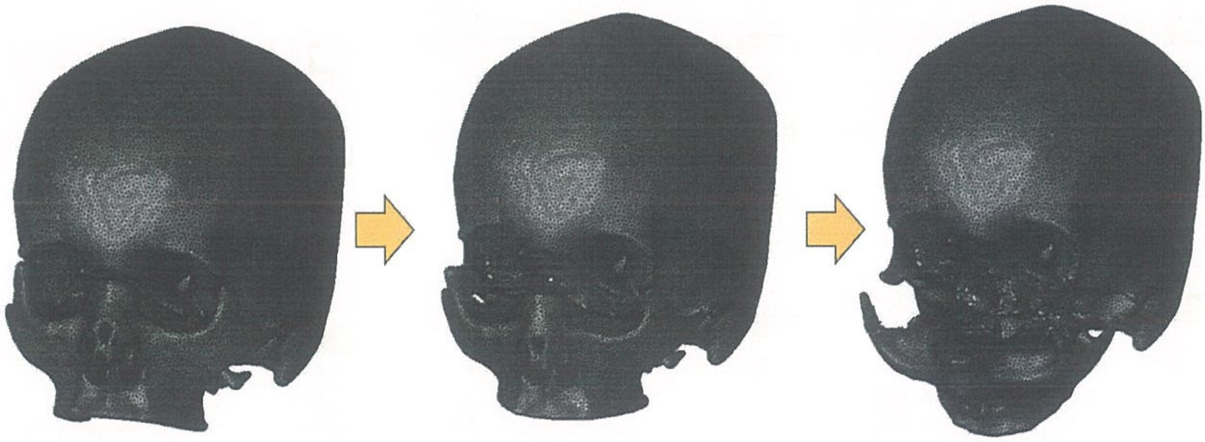

Fig. 3. Down-fracturing was simulated by applying a 98 N load on the bilateral basal floor in the inferior direction.

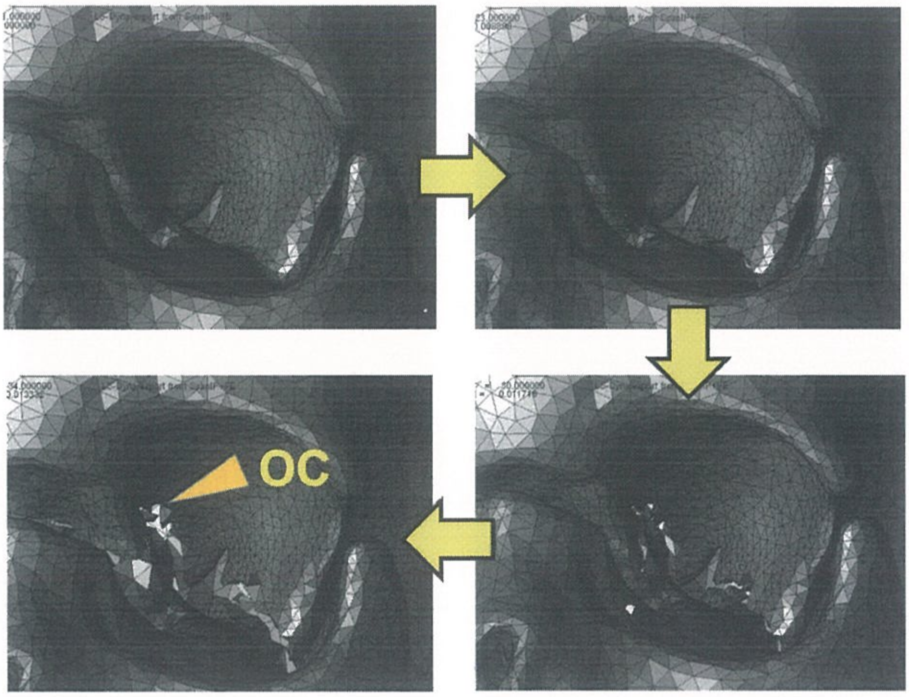

Fig. 4. In the process of down-fracturing, irregular fracture can develop inside the orbit, involving the optic canal (OC) in some cases.

Though Akita's excellent study contributes greatly to increasing safety in performing Le Fort 3 osteotomy, it does not address how the style of the orbital wall separation affects the risk of complications. Carotid-cavernous fistula and blindness — two serious complications of Le Fort 3 osteotomy — are caused by injury to the pyramidal process of the palatal bone and the optic canal, respectively. These structures are located at the tip of the orbital cone. When down-fracturing is performed with insufficient separation of the orbital walls, irregular fracture can develop inside the orbit, affecting these structures. As a result, the above-stated complications can occur. Viewed from this perspective, the separation of the orbital wall should be considered as important a process as pterygomaxillary dysjunction. This study focuses on the orbital-wall separation.

This study employs finite-element simulation as its main method. Experiments on actual cadavers — as carried out in some

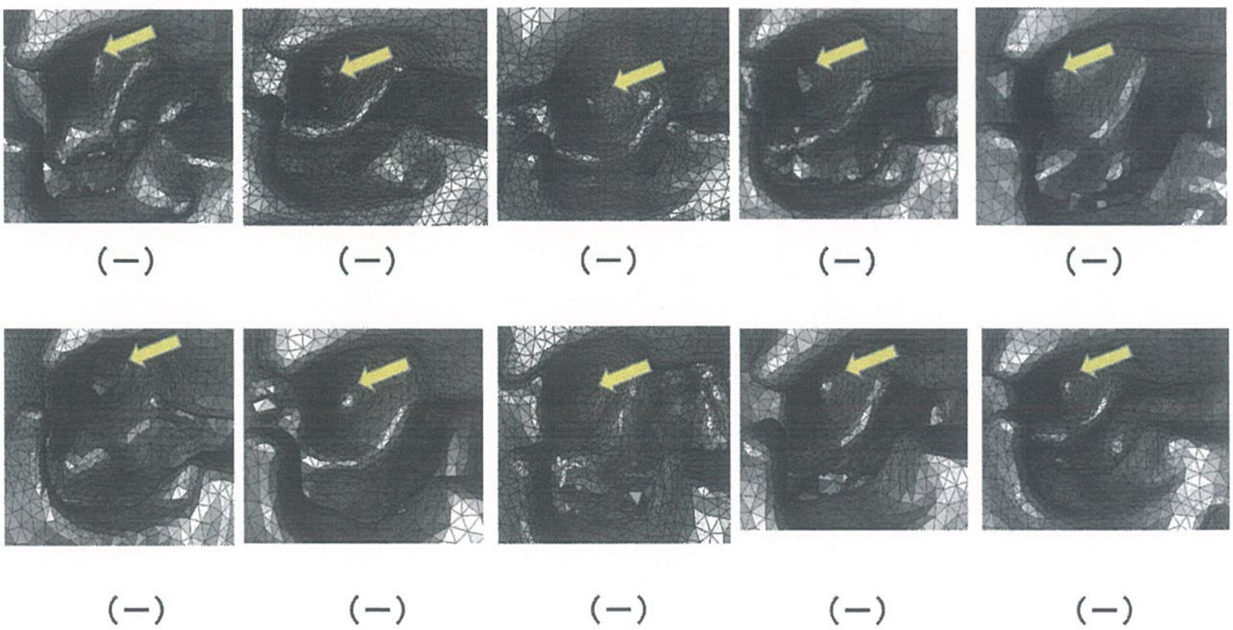

Fig. 5. The conditions of the orbit after down-fracturing in the Type 1 group. The (−)/(+) under each picture indicates the absence/presence of optic canal (shown with arrows) involvement in irregular fracture (likewise in Figs. 6–8). Damage to the optic canal did not occur in the Type 1 group.

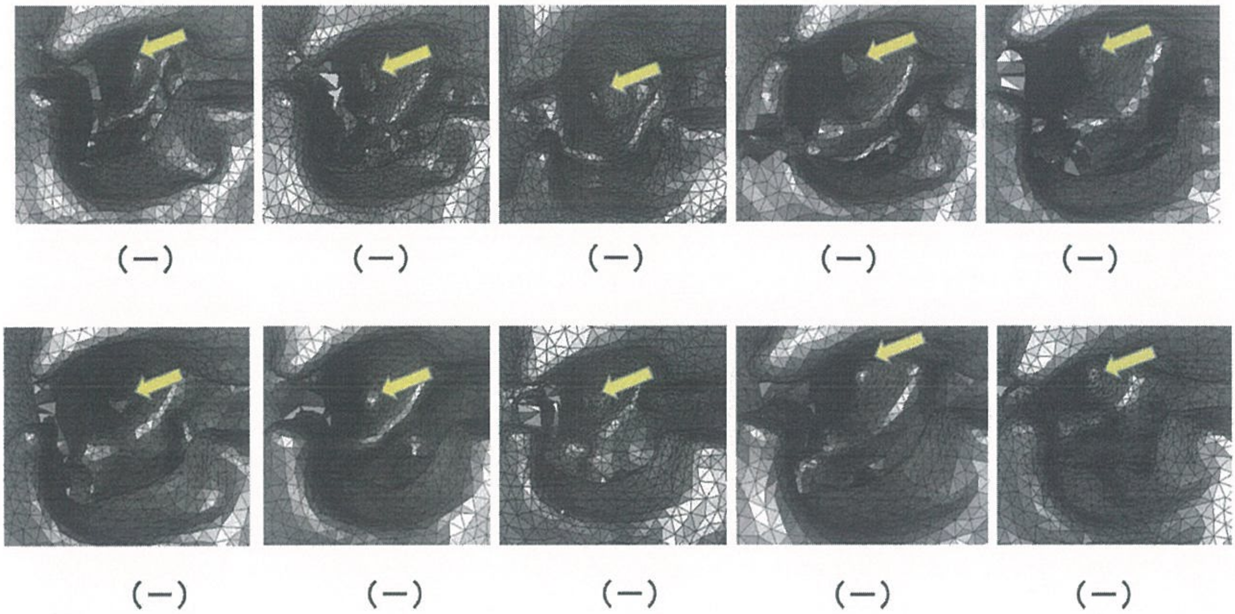

Fig. 6. The conditions of the orbit after down-fracturing in the Type 2 group. Damage to the optic canal did not occur.

of the above studies — might appear more convincing than simulation. However, viewed from the ethical viewpoint of present-day Japan, and probably in many other countries, damaging fresh cadaver skulls is problematic even for scientific purposes. In contrast, dynamic simulation on skull models has few ethical problems. Finite-element simulation is an established technique in the medical field, and is used for biomechanical studies regarding skull bones (Nagasao et al, 2009, 2010), the thorax (Nagasao et al., 2007, 2010), and skin (Nagasao et al., 2013). On the other hand, since finite-element analysis relies on theoretical calculation, the validity of the models must be proven. The validity of this study's models is demonstrated by our previous studies regarding skull bone fractures (Nagasao et al., 2006, 2009, 2010).

Our findings showed that the optic canal broke in 40% of the Type 4 cases, demonstrating that when the separation of the lateral wall is incomplete, irregular fracture is highly likely to occur inside the orbit. The reason for this phenomenon is discussed here. The lateral orbital wall consists of the greater wing of the sphenoid bone and the zygoma. When the facial cranium is forcibly pushed downward, fracture can occur at any point on the lateral wall, if it is not separated. These irregular fractures can advance to the greater wing of the sphenoid bone and, further, to the optic canal (Fig. 9).

On the other hand, our results show that optic canal injury is unlikely to occur in the Type 2 and Type 3 separations. Why does optic canal injury not occur in these patterns? The medial and inferior orbital walls are thinner than the lateral wall. Accordingly,

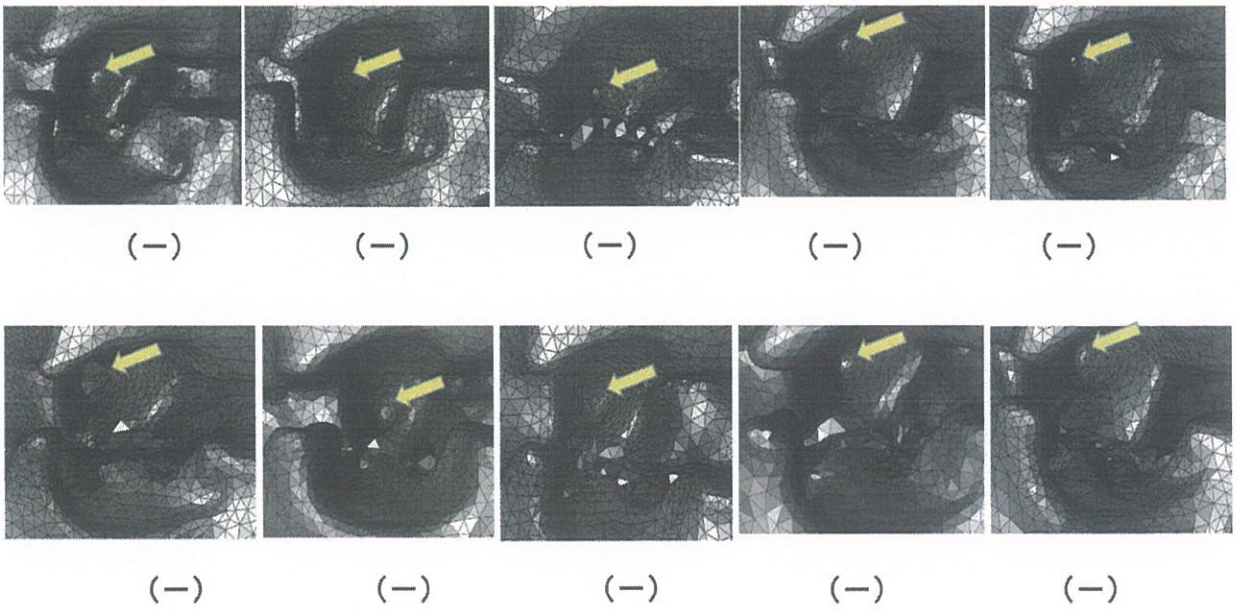

Fig. 7. The conditions of the orbit after down-fracturing in the Type 3 group. Damage to the optic canal did not occur.

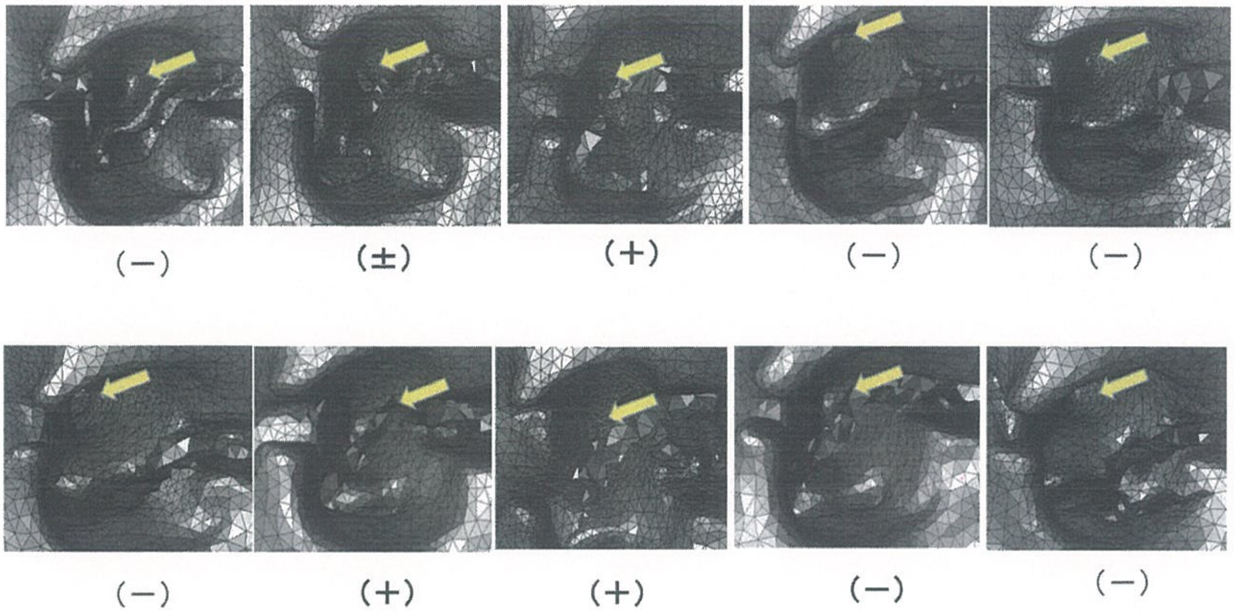

Fig. 8. The conditions of the orbit after down-fracturing in the Type 4 group. Damage to of the optic canal occurred in four of the ten cases.

Table 1
Orbit osteotomy types and optic canal fracture frequencies.

Study group	Frequency of optic canal fracture
Type 1	0/10
Type 2	0/10
Type 3	0/10
Type 4	4/10

they are fragile and break easily when they are distorted, even when they are unseparated. Hence, irregular fracture is unlikely to be transferred to surrounding regions, and the optic canal is rarely damaged.

Based on our findings, we conclude that complete separation of the lateral wall reduces the risk of optic canal injury and subsequent blindness. Compared with the pterygomaxillary junction, it is generally easier to place the lateral orbital wall under direct observation to work on during surgery. However, the working space to separate the orbital walls is often narrowed due to growth retardation of the orbit in patients with craniosynostosis. In such situations, separation of the medial and inferior walls can be omitted if access is difficult. Even if these walls are not separated by direct maneuver, the optic canal is not likely to be damaged in down-fracturing. On the other hand, separation of the lateral wall is strongly recommended to avoid blindness. Thus, the findings of this study may contribute to safe and effective performance of Le Fort 3 osteotomy.

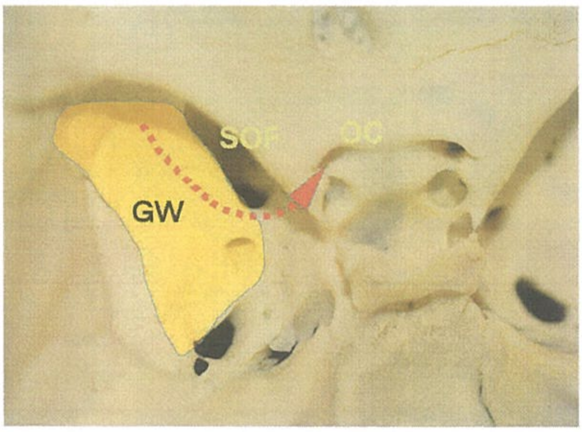

Fig. 9. When the lateral wall is unseparated, irregular fracture can occur in the greater wing of the sphenoid bone (GW) and advance to include the optic canal (OC). SOF indicates the superior orbital fossa.

5. Conclusion

Blindness can occur when the optic canal is damaged during down-fracturing in Le Fort 3 osteotomy. By performing simulation of down-fracturing in finite-element skull models, this study elucidates whether or not the risk of optic canal injury varies depending on the style of orbital wall separation. When separation of the lateral wall is incomplete, the optic canal is likely to be damaged during down-fracturing. So, it is recommended to assure complete separation of the lateral orbital wall in Le Fort 3 osteotomy.

Conflicts of interest

None.

Acknowledgment

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