Comparative analysis of miniplate design and metal magnesium screw ECAP against titanium

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Abstract: In the internal fixation management of maxillofacial fractures, placement of miniplates and screws is necessary until bone repair occurs. Magnesium has the potential for use as a miniplate and screw for the jaws due to its biocompatibility and biodegradability, so that reoperation to remove the miniplate and screw is not necessary. The equal channel angular pressing (ECAP) process is a method to control the corrosion rate of magnesium and increase the mechanical properties. When constructing the miniplate and screw design from ECAP magnesium, referring to the safety factor of the titanium design that already is being used, adjustments must be made according to the characteristics of magnesium so that damage can be avoided. We compared the characteristics of the magnesium ECAP miniplate and screw design against those of titanium. For this study, we used the finite element method, which consists of a displacement formula to calculate component movement, strain, and pressure under internal and external load. Afterwards, the magnesium ECAP miniplate and screw design was subjected to a loading simulation that was analyzed according to the von Mises theory. After stress simulation testing, the magnesium ECAP miniplate and screw, which was expected to be used in the management of maxillofacial fractures, was engineered to reduce the stress received. The design was divided into two types: In type 1, the number of screws was increased to eight, and the total weight of the miniplate and screw was 118.212 mg. In type 2, the diameter of the screw head was made larger than their original shape so that the total weight was 169.414 mg. The type 1 alternative design of the magnesium ECAP miniplate and screw could be more effective in the management of maxillofacial fracture.

1. Introduction
Trauma in the maxillofacial region is encountered commonly in oral surgery and can be caused by traffic accidents, sports, or physical violence. Therefore, optimal efforts should be made to restore the anatomical and aesthetic forms and functions of the soft and hard tissues of the maxillofacial region [1]. Management of maxillofacial trauma using miniplates and screws aims to obtain good immobilization of the fracture fragments. This is based on some important principles of consideration in fractures and bone healing, including adequate vascularization, anatomical reduction, and immobilization of the bone segment [2,3]. Fixation systems are used to obtain stabilization of the fragments so as to restore function of the maxillofacial bone. These systems were introduced in 1958 by Arbeitsgemeinschaft für Osteosynthesefragen (AO), where initially the miniplate and screw materials used were made of chromium cobalt and stainless steel [4,5].
Luhr developed a titanium material, which then became used widely because it had better biocompatibility to the body than other previously used materials for miniplates with the principle of compression and dynamic compression. Titanium then was applied to the maxillofacial skeleton in 1977, and Spießl popularized the application of a dynamic compression miniplate on mandibular bone using techniques reported by the Arbeitsgemeinschaft für Osteosynthesefragen-Association for the study of Internal Fixation (AO-ASIF). In 1978, Champy used titanium in the treatment of mandibular angular fractures by using a miniplate placed in the tension zone, which is superior to the external oblique ridge and the inferior part of the ramus, where it was secured by two screws placed on each side of the fracture line to avoid damage to the dental and neurovascular structures with good results [4]. The Champy method also is called the functionally stable method. Until now, titanium has become the primary choice of material for fixation in trauma cases. It has strong mechanical, biological, and anti-rust properties, and it is biocompatible. Excess metal material can accept loads with high mechanical strength. However, the disadvantage of this material is that it has a modulus of elasticity that is incompatible with bone so as to cause shear strength, which leads to failure of the fixation and immobilization [6].

In addition, the cost of titanium is still high, which can become an obstacle for patients to obtain the ideal fracture treatment. Titanium cannot be reconstituted by the body and sometimes requires reoperation for removal. Therefore, miniplates and screws composed of resorbable materials have been developed and reported since 1971, and they began to be used in pediatric craniofacial surgery in 1996. There are several types of resorbable materials, including polyactic acid (PLA) and polyglicolic acid (PGA). PGAs, which are resorbed to carbon dioxide, have a faster resorption time than PLAs, which are resorbed into lactate. According to Fonseca, the most common complications regarding use of this material are palpability, body reaction to foreign matter, effusion (release of gas), and infection. From the standpoint of strength and stabilization, the resorbable/polymer material is not as good as titanium, and according to the AO principle, fracture stabilization is essential for fracture healing. Also, the polymer material is more expensive than titanium, which becomes a further obstacle for patients.

Some requirements that must be met are that resorbable materials must have strong mechanical strength during bone healing and a resorption speed in accordance with the speed of bone healing, and it must be biocompatible and safe [7,8]. Due to the lack of strength and stabilization of polymer material, studies have been done on the use of metal magnesium to construct miniplates and screws. Compared with other metal materials, magnesium is a light metal with an elastic modulus and compressive yield strength most similar to bone [6].

Because the strength of the polymer is not as good as that of titanium, and surgical results are based on the AO principle that there must be good stabilization during fracture healing, we compared the characteristics of miniplates and screws designed with titanium and magnesium equal channel angular pressing (ECAP) materials.

2. Research methods
2.1 Research design

In this laboratory experimental study, a load stimulation test was performed at the Mechanical Engineering Laboratory, Faculty of Engineering, Universitas Indonesia between October and December 2015.

2.2. Assumptions of assignment

The assumption taken was the condition where the screw is weighed down by the miniplate. Under these conditions, the load will be concentrated on the screw neck region in the direction parallel to the screw head. In addition, we analyzed the phenomenon occurring when the screw is taken into the jaw bone, whereas the miniplate is assumed to be withdrawn with the same force on both ends. In this manner, we attempted to simulate the operational conditions that screws and miniplates will encounter.
2.3. Tools and materials

We used a Toshiba Qosmio F750 series laptop with an Intel® Core™ i7-2630QM CPU, a 2 GHz processor, and 4 GB of RAM and Autodesk Inventor Professional 2015 software. We also used a screw and miniplate model whose size was assumed to be the same as that of models on the market. The models were of a curvature mesh type with a maximum size of 0.05 and a minimum of 0.01 and were of high quality, because the geometry number was small.

2.4. Working steps

The miniplate and magnesium ECAP screw model was designed on the basis of various reports on the properties and design of miniplates and screws. Then, simulation of the miniplate and screw design was done using stress analysis software. Finally, stress distribution was performed to obtain the design/geometry of the magnesium ECAP miniplates and screws, so that we could determine the maximum load acceptable without causing deformity.

In this study, we designed the ECAP magnesium material by referring to the design of titanium used in maxillofacial fracture cases, which is a straight-shaped miniplate consisting of four holes with spaces between the second, third, and fourth holes of the miniplate. This was one of the earliest standard forms of miniplates and was easy to design for the magnesium ECAP material. Regarding the screw design, we chose an auto-drive screw type with a size of $1.5 \times 5$ mm so as to facilitate the operator in direct installation of the screw without removal of bone using burs, avoiding heat from the burs to the bone, and shortening the working time.

For this study, we used the finite element method of the displacement formula to calculate displacement of the components, strains, and pressures under internal and external loads. The geometry under analysis used tetrahedral (3D), triangle (2D), and beam elements and was solved by either sparse solvers or direct iterations. The failure condition used was the von Mises theory, which is an equation that takes every value of shear stress and principal stress, and produces a “von Mises value of stress” scale that can be compared with the yield of the material. If the von Mises value of stress was greater than the yield strength, then the part failed according to the criterion. However, if the result was less than the yield strength, then the part was said to be safe, and did not fail.

3. Results

This study was conducted to compare the ECAP magnesium miniplate and screw design with that with titanium. ECAP magnesium has different mechanical properties than titanium, which is used commonly (Figure 1). Therefore, it was necessary to construct a special design.

The design of the screw used was divided into two types. In one screw design (type 1), the shape and size were adjusted according to those of screws that are used commonly in the management maxillofacial fractures (Figure 2). The number of screws was increased to eight. The second screw (type 2) was engineered in order to adjust the tension/stress received when the material used was changed to ECAP magnesium (Figure 3). The diameter of the screw heads was changed to two times larger than the original size. The following are the dimensions of screws designed on the basis of commercial titanium and ECAP magnesium alternative screw designs:
Figure 1. View of titanium commercial screw, (a) Top view, (b) Front view

Figure 2. View of type 1 alternative screw, (a) Top view, (b) Front view
From the miniplate and magnesium ECAP screw simulation, some results were achieved indicating that the ECAP design alternatives can help reduce stress to prevent damage:

1. **Type 1 alternative design by increasing the number of screws to eight on one series of screws and miniplates.**
   Mass of each screw: 5596 mg
   Miniplate mass: 73.444 mg
   Therefore, the total mass for one series of miniplates and screws was
   \[8 \times 5596 \text{ mg} + 73.444 \text{ mg} = 118.212 \text{ mg} .\]

2. **Type 2 design alternative by changing the diameter of the ECAP magnesium screws twice, so the number of screws used in one series of miniplates remains 4.**
   Mass of each screw: 23.437 mg
   Miniplate mass: 75.666 mg
   Therefore, the total mass for one series of miniplates and screws is
   \[4 \times 23.437 \text{ mg} + 75.666 \text{ mg} = 169.414 \text{ mg} .\]

### 4. Discussion

#### 4.1. Screw simulation results

| Item Design | Ti (Commercial) in MPa | Mg (referring to Ti geometry) in MPa |
|-------------|------------------------|-------------------------------------|
| 1           | 39.75                  | 38.03                               |
| 2           | 8.698                  | 7.894                               |
| 3           | 64.45                  | 36.64                               |
After simulation of the screws with the same geometry by loading the titanium and magnesium screws, the maximum stress value for magnesium was lower than that for titanium (Table 1). This suggested that magnesium can receive better loading than titanium.

| Item design       | Ti (Commercial) | Mg (referring Ti geometry) | Mg Alternative 1 (proposed) | Mg Alternative 2 (proposed) |
|-------------------|-----------------|-----------------------------|-----------------------------|-----------------------------|
| Section 1         | 7.67            | 6.8                         | 5.78                        | 8.75                        |
| Section 2         | 15              | 15                          | 5.39                        | 15                          |
| Section 3         | 4.66            | 6.63                        | 6.32                        | 6.79                        |

Using the stress analysis feature of the Autodesk Inventor 2015 program, the safety factor was obtained for commercial titanium, commercial magnesium, alternative magnesium type 1 (proposed), and alternative magnesium type 2 (proposed) screws (Table 2).

| Item design       | Ti (Commercial) in MPa | Mg (referring to Ti geometry) in MPa | Mg (proposed) in MPa | Mg (proposed) in MPa |
|-------------------|------------------------|-------------------------------------|----------------------|----------------------|
| Section 1         | 39.75                  | 38.03                               | 42.77                | 28.14                |
| Section 2         | 8.968                  | 7.894                               | 44.43                | 14.72                |
| Section 3         | 64.45                  | 36.64                               | 36.84                | 31.65                |

Table 3 shows the maximum stress values received by each commercial titanium, commercial magnesium, alternative magnesium type 1 (proposed), and alternative magnesium type 2 (proposed) screws. From the results of the above stress analysis, the stress received by the screw in the type 1 alternative design (increased number of screws with commercial geometry form) is greater than that received by the type 2 alternative screw (new screw geometry).

4.2. Discussion about miniplate simulation

| Item design       | Ti (Commercial) (MPa) | Mg (referring to Ti geometry) (MPa) |
|-------------------|-----------------------|------------------------------------|
| Section 1         | 65.5                  | 66.01                              |

The miniplate with commercial geometry can receive stress (Table 4). However, commercial geometry miniplates made of titanium are stronger than those made of magnesium material.

| Item design       | Ti (Commercial) | Mg (referring to Ti geometry) | Mg Alternative 1 (proposed) | Mg Alternative 2 (proposed) |
|-------------------|-----------------|-----------------------------|-----------------------------|-----------------------------|
| Section 1         | 4.21            | 1.36                        | 4.38                        | 4.08                        |

Table 5 shows the value of the safety factor resulting from stress analysis conducted using the Autodesk Inventor 2015 program for commercial titanium, commercial magnesium, type 1 magnesium, and type 2 alternative miniplates.

| Item design       | Ti | Mg (referring to Ti) | Mg | Mg |
|-------------------|----|----------------------|----|----|

6
Table 6 shows the maximum stress value received by commercial titanium, commercial magnesium, type 1 magnesium, and type 2 magnesium miniplates. The stress received by the type 1 magnesium miniplate was smaller compared with that of the type 2 alternative miniplate.
5. Conclusion
There are two types of design alternatives for ECAP magnesium miniplate and screw. In the type 1 alternative, the number of screws was increased to eight, whereas in the type 2 alternative, the diameter of the screw heads was changed to two times larger than the original size. Although the type 2 alternative had the advantage of screw size and robustness compared with the type 1 alternative, it became less effective. Our results also showed that the total mass of the screw and miniplate used in the type 2 alternative (169.414 mg) was heavier compared with that of the type 1 alternative (118.212 mg).

6. References
[1]. Prein J 1983 Manual of Internal Fixation in the Cranio-Facial Skeleton: Techniques Recommended by the Ao/Asif-Maxillofacial Group: Springer.
[2]. Haerle F, Champy M and Terry B 2009 Atlas of Craniomaxillofacial Osteosynthesis. 2e edition. Thieme; Stuttgart, New York.
[3]. Bowers D G, Jr and Lynch J B 1977 Management of facial fractures South Med J 70 910–8.
[4]. Ehrenfeld M, Manson PN and Prein J 2013 Principles of Internal Fixation of the Craniomaxillofacial Skeleton Trauma and Orthognathic Surgery. AO Foundation. Thieme; Stuttgart, New York.
[5]. Kellman Robert M and Marentette L 1995 Atlas of Craniomaxillofacial Fixation. Raven Press, Ltd; New York.
[6]. Staiger MP, Pietak Am, Huadmai J and Dias G 2006 Magnesium and its alloys as orthopedic biomaterials: a review Biomaterials 27 1728–34.
[7]. Gu XN and Zheng YF 2010 A review on magnesium alloys as biodegradable materials. Heidelberg, Allemagne: Springer.
[8]. Xin Y, Hu T and Chu PK 2011 In vitro studies of biomedical magnesium alloys in a simulated physiological environment: a review Acta Biomater 7 1452–59.