Using a modal analysis system, we carried out a comparative assessment of the vibratory properties of the maxillary dentition of a human dry skull with a different distal end of a mouthguard. Mouthguards used in this study were: 1. a mouthguard covering up to the third molar (8MG), 2. the second molar (7MG), 3. the first molar (6MG), and 4. the second premolar (5MG).

To identify the modal shape, the frequency response functions were recorded on a fast Fourier transform analyzer from the force signal impacted with a vibration generator and the response signal picked up using a laser-doppler vibrometer. The transient response waves were obtained throughout the transient response simulation procedures after curve-fitting procedures. Mean decay rates (sec\(^{-1}\)) of the transient response waves were calculated for the anteriors, premolars and molars, and compared among different sets of experimental conditions.

The decay rates became lower as the distal end of a mouthguard was short. The decay rates with 8MG, 7MG and 6MG (anteriors) exceeded the no mouthguard’s decay rate + 2S.D. values. These results imply that a mouthguard should distally cover up to the second molar at least to ensure efficient absorption and/or dispersion of a traumatic force.

Key words: Mouthguard, Modal analysis, Orofacial injury, Maxillary teeth, Sports dentistry

Introduction

Athletic mouthguards are commonly worn during contact sports to prevent orofacial injuries such as bruises, lacerations, tooth fractures, dislocations, avulsions, and jaw fractures\(^1,2\). Concerning the optimal shape of a mouthguard, current literature states that the mouthguard should cover all the remaining teeth except for erupting wisdom teeth in the maxillary arch, except in patients with mandibular prognathism\(^3\). However, we know that players often wear mouthguards that do not cover the posterior teeth. Also, in our daily practice, we hear complaints from some players that they experience discomfort and nausea when wearing custom-made mouthguards that cover all the teeth in the maxillary arch.

Many authors comment that one of approach to avoiding such complaints would be to cut off the distal ends of mouthguards at the second premolars\(^1\) or the first molars\(^1,4,6\). However, this suggestion is based on clinical experience rather than scientific evidence, since no experiments have been done to test whether...
such shortened mouthguards have the advantageous properties of ideal mouthguards.

A previous report has suggested that players wearing a cut-off mouthguard might be at greater risk than other players using custom-fitted guard that covers all the teeth. Therefore, the aim of this study was to obtain scientific data on the effects of shortening the distal end of a mouthguard. Mouthguards used in this study were: 1. a mouthguard covering up to the third molar (8MG), 2. the second molar (7MG), 3. the first molar (6MG), and 4. the second premolar (5MG). Through modal analysis including transient response simulation, which is a fundamental method for theoretically predicting and identifying how each part of an object will vibrate in response to a given impact force, we comparatively assessed the vibratory properties of the maxillary dentition of a human dry skull among 4 different distal ends of mouthguards.

**Materials and Methods**

1. **Dry skull**
   The test object was an intact adult dry skull with a full set of natural teeth. All the sockets and sutures of the maxilla were filled with cyano-acrylic adhesive to prevent rattling.

2. **Mouthguard**
   The mouthguard, which covered up to the third molar (8MG), was made of Molteno, the regular type of polyolefin mouthguard material (Molten Medical Co., Tokyo, Japan; Elasticity modulus (Stiffness): $1.0 \pm 0.2 \times 10^7$ Pa, JIS-A hardness: $77 \pm 3$, Tensile strength: $1177 \pm 490 \times 10^4$ Pa, Elongation: $850 \pm 100\%$) using a stone cast. The extension of the mouthguard reached 10 mm labio-buccally below the edge of alveolar bone and to the edge of palate on the palatal side. The labio-buccal, palatal and occlusal portions were all 3 mm thick.

3. **Experimental procedures**
   This experiment was performed in a laboratory at 24°C and humidity of 70%.
   The experimental setups (Fig. 1) were all identical to those described in Morikawa et al.’s report. The dry skull was cushioned with a sponge in this study. Prior to the experiment, the frame shape of the maxillary arch of the dry skull was determined by scanning the 26 measurement points on the tooth surfaces using

![Diagram of the experiment for modal analysis of the maxillary teeth.](image-url)
SURFLACER, non-contact and high-speed 3-D shape measurement system (UNISN Inc., Osaka, Japan). The X, Y and Z coordinate axes in this study were defined as shown in Figure 2.

To detect laser beams from the measurement points using the laser-doppler vibrometer, the mouthguard had 25 holes, each 3 mm in diameter, except for the hole in the right central incisor, which was 5 mm in diameter to allow a driving rod to pass through. A total of 26 measurement points were set up. Reflective marks were placed on the measurement points to gain more sensitive response signals.

First, modal analysis was performed on the maxillary dentition of the dry skull itself using a periodic random excitation force signal applied to the right central incisor. The summed average of 32 frequency response functions (frequency range: 0–2 kHz) was measured at each measurement point of the maxillary dentition using the FFT analyzer, and was then curve-fitted using Vibrant Gen software (Marubeni Solutions Co., Tokyo, Japan). The modal shape of the maxillary dentition was drawn using the 26 curve-fitted functions.

Second, the above-described modal analysis was carried on the dry skull using the 8MG mouthguard (16.15 g). The same experiment was in turn repeated using the 7MG mouthguard (14.40 g), the 6MG version (12.15 g) and the 5MG version (9.57 g). These different mouthguards were created by, first cutting off the third molar part of the 8MG, then the second molar part of the resultant 7MG version, and then the first molar part of the resultant 6MG version. Finally, transient response simulations were carried out using the Vibrant Gen software assuming the right central incisor was impacted with a force of 98 N in the direction of the X-axis. Transient response waves of the anteriors and posteriors (premolars and molars) were individually computed in the X-axis and Y-axis directions.

4. Data analysis

Data analysis was performed using Dampcal software (Marubeni Solutions Co., Tokyo, Japan). Decay rates were calculated from 10 positive peak displacement values, which had been detected from the transient response wave at each measurement point (Fig. 3). To avoid plotting inconsistency error, the average of 4 repeated measurements was processed for each measurement point. Mean decay rates at the anteriors, premolars and molars were compared among the different experimental conditions (8MG, 7MG, 6MG, 5MG).

Results

For no mouthguard (NMG), the decay rates at the anteriors, premolars, and molars were 72.90 ± 1.80, 68.64 ± 3.91, and 70.75 ± 1.90 sec⁻¹, respectively.

The decay rates at the anteriors for 8MG, 7MG, 6MG, and 5MG were 107.00 ± 10.70, 87.31 ± 3.62, 81.99 ± 5.38, and 74.24 ± 3.89 sec⁻¹, respectively (Fig. 4). The decay rates at the premolars for 8MG, 7MG, 6MG, and 5MG were 100.96 ± 2.79, 87.62 ± 3.89, 73.38 ± 2.51, and 70.42 ± 6.24 sec⁻¹, respectively (Fig. 5). Also, the decay rates at the molars for 8MG, 7MG, 6MG, and 5MG were 100.72 ± 5.39, 89.21 ± 9.61, 73.20 ± 1.67, and 70.18 ± 2.37 sec⁻¹, respectively (Fig. 6).
Discussion

The natural frequencies we obtained under experimental conditions in this study are shown in Table 1. Six resonance peaks were identified in 6MG, and 5 in others. Natural frequencies of over 1000 Hz were dampened in all of the experimental conditions as compared with NMG (Fig. 7). These results supported Morikawa et al.’s findings.

A higher decay rate value indicates that vibration will cease more quickly after applying an impact. Our study showed that the decay rate became lower as the distal end of a mouthguard was short. These results implied that it would be difficult to cease the vibration by shortened the distal end of a mouthguard. For 8MG and 7MG, the decay rates at the anteriors and posteriors exceeded the NMG’s decay rate + 2S.D. values, considering that a mouthguard should distally cover at least the second molar to sufficiently absorb and/or disperse any traumatic force arriving from the frontal direction. Also, the decay rate at the anteriors for 6MG exceeded the NMG’s decay rate + 2S.D. value. Because many authors have reported that dental trauma is significantly more often inflicted on the maxillary anterior teeth in the permanent dentition, we pointed out that mouthguards would distally cover the first molar to give at least some degree of anterior protection.

A previous report has suggested that players wearing a cut-off mouthguard might be at greater risk than other players using custom-fitted guard that covers all the teeth, since 10 of 11 players wearing the cut-off mouthguards suffered mild concussion. Also, a study of
American Football players reported that 71 of 75 players (95%), who suffered head injuries, were wearing mouthguards during play, but 63 of these players (89%) were wearing incomplete over-the-counter mouthguards (boil-and-bite type: 42, cut-off type: 12, and stock type: 9). Since our study suggests that a shortened mouthguard such as 5MG is unable to provide rapid damping of vibration of maxillary dentition, it is seemed that shortened mouthguards do not possess the advantageous properties of ideally shaped mouthguards.

Of course, the real movement of natural maxillary dentition when a mouthguard is worn cannot be accurately illustrated using the present simulation study. Several researchers\textsuperscript{12,13} have recently criticized the direct application of modal analysis to living human subjects. In the near future, enhanced forms of modal analysis may be able to measure more accurately the vibratory properties of human maxillary dentition when protected by a mouthguard.

References