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Mouthguards: difference in longitudinal dimensional stability between single- and double-laminated fabrication techniques

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Miura J, Maeda Y, Machi H, Matsuda S. Mouthguards: difference in longitudinal dimensional stability between single- and double-laminated fabrication techniques. © Blackwell Munksgaard, 2006.

Abstract – Though the use of mouthguards (MGs) has increased with the increase in sporting activities, little is known about the influence of their fabrication methods on longitudinal dimensional stability. The objective of this study was to compare the difference in the longitudinal dimensional stability between single and laminated MGs. Single-layer MGs were made from a 4.0 mm thick ethylene vinyl acetate (EVA) sheet and laminated MGs were made from two 2.0 mm thick sheets of EVA. MGs were kept in a 37°C water bath for 60 h, equivalent to the time period of 3-months inter-oral use. MG deformation was analyzed by measuring designated points on the MG border using a profile projector (J-12, Nikon Inc., Tokyo, Japan) before and after the water immersion. A finite-element model was also created to examine the time course of stress accumulation during the sheet forming process using Finite Element software. Longitudinal deformation was smaller in the laminated MGs than in the single-layer MGs in the anterior area ($P < 0.05$). Finite element method (FEM) analysis also showed the largest stress accumulation in the anterior incisal area where deformations were mainly observed. Laminated double layer MGs have advantages over single-layer MGs in terms of longitudinal stability due to lower stress accumulation during the fabrication process.

Key words: mouthguard; dimensional stability; laminate; finite element method

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The use of mouthguards (MGs) has increased with the increase in sporting activities, such as rugby football, American football, boxing and so on (1, 2). However, little is known about the influence of the manufacturing process on the accuracy of fit or the dimensional stability of MGs (3, 4) which may be closely related to their trauma prevention capability (5) as well as wearability.

The advantage of custom-made MGs over so-called over-the-counter or boil-and-bite MGs have been clarified by previous reports (6). Custom made MGs can be classified into two categories, namely the single-layer MG (Fig. 1a) and laminated MG (Fig. 1b). Laminated MGs have several advantages over single-layer MGs: the freedom for thicknesses for parts where strength is needed (5), such as the anterior labial part or the posterior buccal part, and freedom for colors or inserting identification (7). The longitudinal dimensional stability of MGs, however, is critical for the promotion of MG usage among athletes, which has yet to be closely examined among the two types of MGs.

Our working hypothesis in this study was that laminated MGs have more longitudinal dimensional stability than single-layer MGs, because of lower stress accumulation during the fabrication process.

The objective of this study was to compare the longitudinal dimensional stability of single-layer and

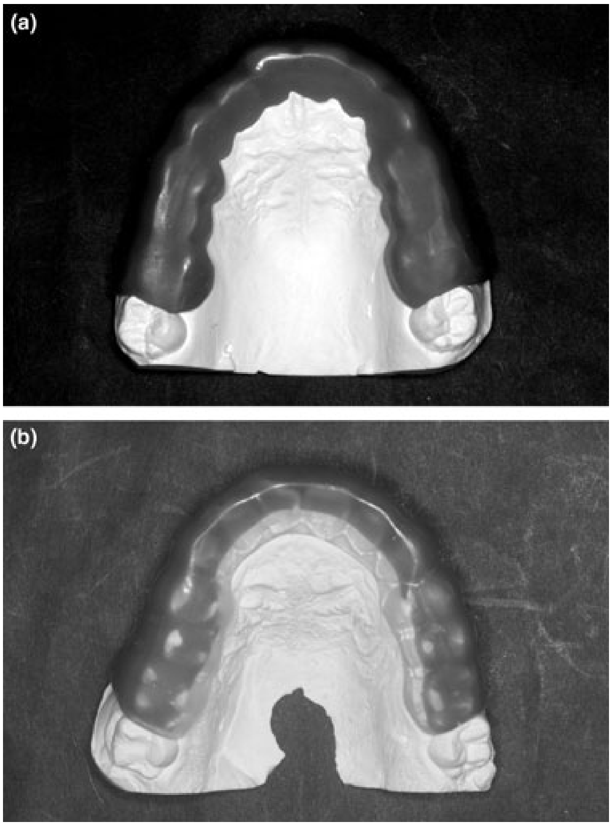

Fig. 1. (a) Single-layer mouthguard and (b) laminated mouthguard.

laminated MGs using warm water immersion tests and three-dimensional finite element analysis.

Materials and methods

Warm water immersion study

Dental stone (New Plaster; GC, Tokyo, Japan) was poured into the mold of a maxillary dental arch model (N350; Nissin Co, Kyoto, Japan). The plaster model was trimmed to construct a master model without an undercut area to prevent MG deformation on its removal from the plaster model (Fig. 2). A silicon mold of the master model was made with silicon impression materials of high durability (DUPLICONE; Shofu Co, Kyoto, Japan) for preparing working models for MG fabrication.

Single-layer (4.0 mm thick) and laminated MGs (2.0 + 2.0 mm thick) (6) were made from ethylene vinyl acetate (EVA) sheets (Erko-flex; Erkodent, Pfalzgrafenweiler, Germany) using a pressure-forming machine (Erkopress; ES-200E, Erkodent, Pfalzgrafenweiler, Germany) on well-dried working models (8). 9 MG specimens were made per design using the single-layer and laminated techniques for a total of 18 specimens. For the fabrication of

Fig. 2. Plaster model (blockout dental arch model).

laminated MGs, the first layer was formed with a 2 mm thick EVA sheet and trimmed to cover only the anterior region, then a second layer was formed with another 2 mm thick sheet placed on to the model with the trimmed first layer, as with the lamination technique (6).

One hour after pressure forming, the EVA sheets were removed and trimmed. MGs were placed in a 37°C water bath for 60 h, which was considered to be equivalent to an average 3-months MG usage in the oral cavity for sporting activities.

MG deformation was analyzed by measuring designated points on the MG border before and after the water immersion period using a profile projector (J-12; Nikon Inc, Tokyo, Japan). Each measurement was repeated five times, and the averaged value was used for statistical analysis. Five different distance parameters between the designated points A–E (Fig. 3) were used in the analysis, which was performed with the Student's *t*-test using SPSS Ver.11.0 (SPSS Inc, Chicago, IL, USA).

Non-linear 3D finite-element analysis

Finite-element models of a working model and a sheet of EVA material were created using computer-assisted design (CAD) software and a pre- and post-processor (J-Vision; The Japan Research Institute Ltd, Tokyo, Japan), and these were also used to examine stress concentration and distribution during the sheet-forming process. One model was designated for single-layer (4 mm thick) formation (Fig. 4a) and an other was for two layer (2 mm + 2 mm) formation with lamination on the incisal edge area (Fig. 4b). The layer covered only the incisal edge of the anterior region and the second layer covered the whole arch and overlapped the anterior region.

The EVA sheet consisted of 3200 isoparametric solid elements. For the laminated model, the EVA

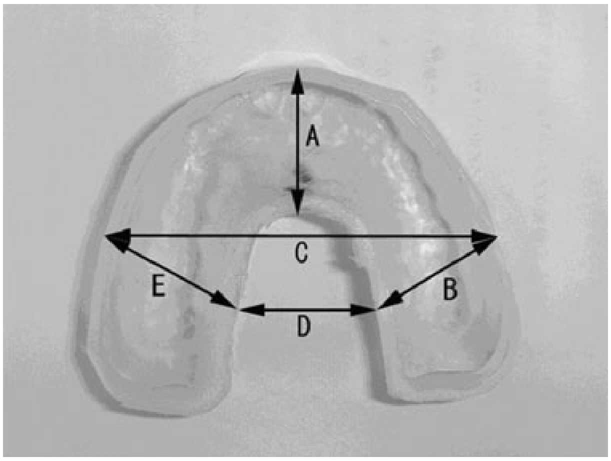

Fig. 3. Measuring point of sample mouthguard Master model showing distances between designed points: (A) mesial, (B) right, (C) buccal, (D) palatal, and (E) left.

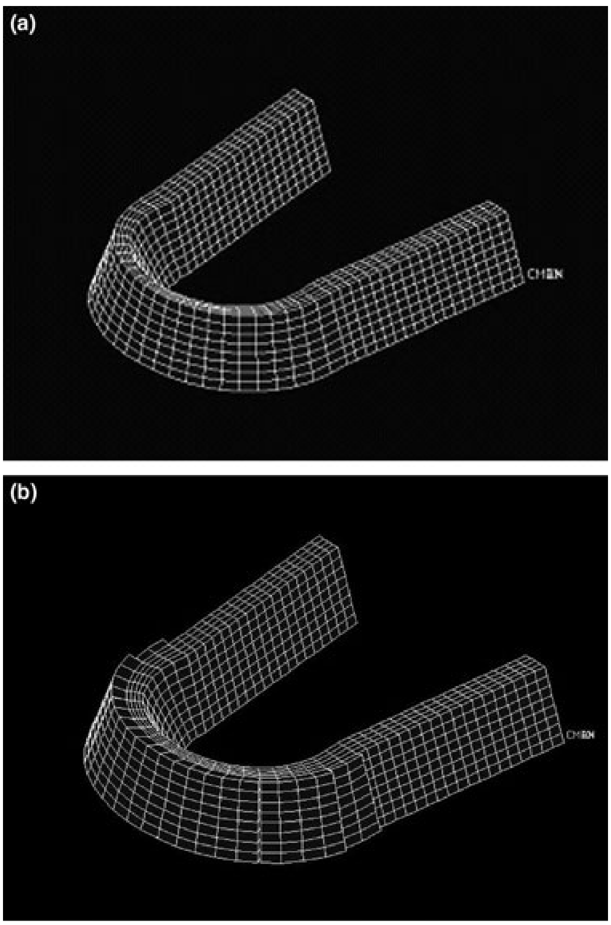

Fig. 4. Model of finite element analysis comparing between single-layer and laminated. (a) Dental arch model (single-layer) and (b) dental arch model (first layer of laminated mouthguard).

sheet of the first layer was trimmed as indicated above and was assumed to have elements the same as the plaster model elements.

As the material properties of EVA during the softening process have not been reported, the material property values at the time of softening at 150°C were used as a reference, Young modulus of 5 MPa and Poisson's ratio of 0.49 were used for the EVA sheet model (9, 10). As the plaster model was designated as a rigid object and the sheet as a deformable object, forming pressure was applied on the upper side of the sheet as air pressure. Constraints were applied to the lower part of the dental arch model. Simulation of the thermoforming process was performed with 3D non-linear analysis software (LS-DYNA; Livermore Software Technology Corp, Livermore, CA, USA) using a supercomputer (SX5; NEC, Tokyo, Japan) at the Osaka University Cyber-Media Center. With this soft-ware, the time-course of the forming process from the softened sheet material to the working model can be calculated step by step. Principal stress levels in the formed EVA sheet elements were analyzed.

Results

Longitudinal deformation with the water immersion test was smaller in laminated MGs than in single-layer MGs at all distance parameters between designated points (Fig. 5). Deformation in the anterior area was significantly larger than in the posterior area ($P < 0.05$).

FEM analysis showed high strain levels in the anterior incisal region and the middle palate area of the model during the forming process (Fig. 6a and b). There was a clear difference between the laminated and the single-layer MGs in terms of the strain level. The single-layer model showed the highest strain level in the anterior incisal region, while the laminated model showed widely distributed strain over the incisal and posterior areas (Fig.. 6a and b). The strain level of the single layer model at the incisal region was

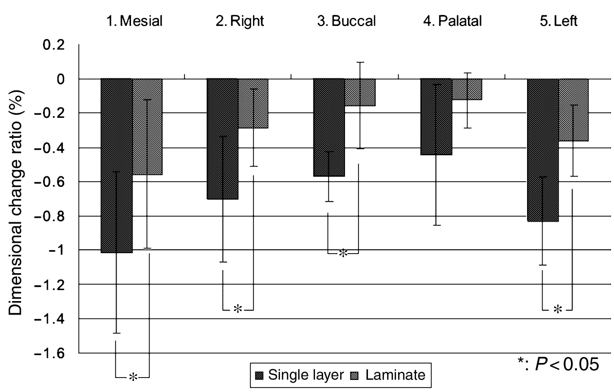

Fig. 5. Results of the water immersion study comparison between single-layer and laminated mouthguards.

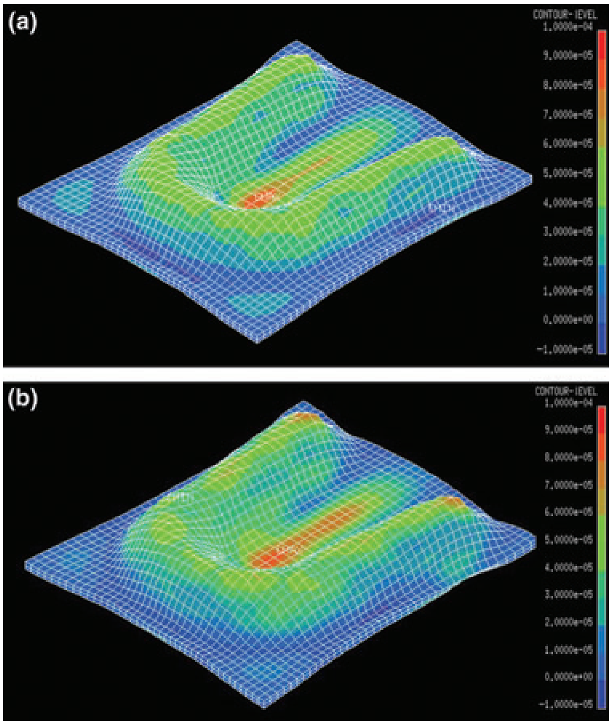

Fig. 6. (a) Single-layer mouthguard analysis result. FEM analysis showing high strain levels in the anterior incisal region and the middle palate area in single-layer mouthguard. (b) Laminated mouthguard analysis result FEM analysis of laminated mouthguard showing lower strain levels than single-layer in the anterior incisal region.

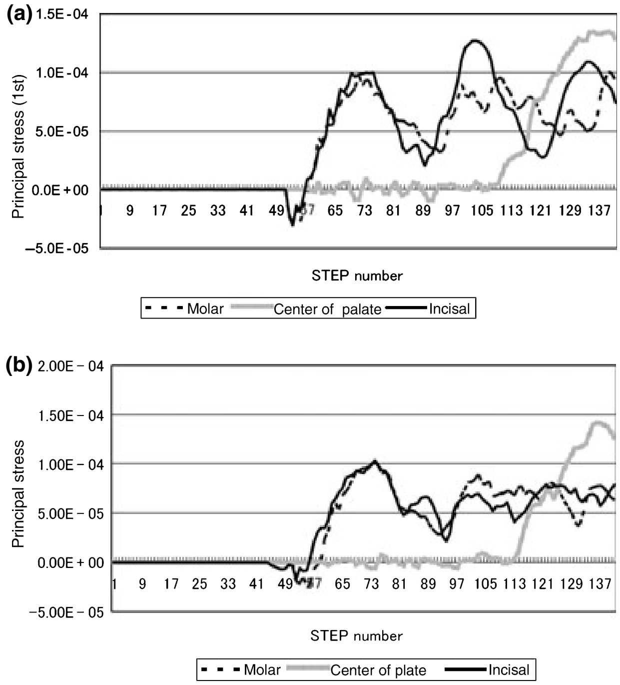

Fig. 7. (a) Step history of principal stress on single-layer mouthguard sheet. (b) Step history of principal stress on laminated mouthguard sheet.

approximately 1.5 to 2 times that of the laminated model.

Figure 7a and b, also show the relationships between the simulation steps and strain level changes in the incisal, posterior and palatal regions during MG fabrication. Compared with the single-layer MG, the laminated MG shows lower strain accumulation during the second layer forming process in the incisal region.

Discussion

MG abrasion and deformation are major problems with prolonged wearing. Deformation is most critical, because it affects the retentive capability of MGs directly (11).

Our working hypothesis in this study was that laminated MGs have more longitudinal dimensional stability than single-layer MGs, because of lower stress concentration during the fabrication process.

Results from the water immersion study indicated lower longitudinal deformation in the laminated MGs than in the single-layer MGs, and that there was a significant difference in deformation between the anterior and a posterior areas. These results indicate that thermoformed MGs have a tendency to deform in the anterior incisal area. This anterior incisal area was the area where the highest strain level was found in the FEM analysis, particularly in the single-layer model.

As the high strain area does indicate the high stress area, even in elastic material such as EVA, the following speculation can be made: the sharp incisal edges of the anterior region maybe the main cause of stress accumulation during the forming process for the first layer of the laminated and the single-layer MGs. The reduction in EVA sheet thickness in the single MG-forming process was largest in the sharp incisal area in the anterior region. We speculated that this part of the sheet is usually pulled or pushed down on both sides of the anterior teeth to a large extent when the softened sheet makes initial contact with the model during the forming process. During the cooling process, the sheet increases in rigidity while internal strain in the formed EVA sheet can accumulate and remain as residual stress. This residual stress can be the main cause of the subsequent deformation observed in the water immersion procedure, which occurs during the process of relaxation.

During fabrication of the second layer of the laminated MG, the sharp incisal edges were covered with the first layer. Due to the elimination of the sharp edges by the first layer, strain might not have accumulated in the anterior region when the second layer was formed, as shown in the FEM analysis. As the accumulation of strain and subsequent residual stress can be smaller in the incisal edge area during the second layer forming process, reduced longitudinal deformation can be expected for laminated MGs, as was indicated in the results of the warm water immersion test.

Although other factors contribute to deformation, such as repeated removal or heavy clenching during MG usage in sports activities (12, 13), manufacturing factors should be more closely examined in further studies, fundamental deformation due to residual stress accumulation during MG fabrication can be minimized by utilizing the lamination technique.

Conclusions

Double layer or laminate mouth guards have advantages over single-layer ones in terms of longitudinal dimensional stability because of smaller residual stress accumulation during the forming process.

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