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Effect of Viscoelastic Deformation of Soft Tissue on Stresses in the Structures under Complete Denture

Fumiaki Kawano*, Kenzo Asaoka**, Kan Nagao* and Naoyuki Matsumoto*

*Department of Removable Prosthodotics, School of Dentistry, University of Tokushima, 3-Kuramoto-cho, Tokushima, 770, Japan

**Department of Dental Engineering, School of Dentistry, University of Tokushima, 3-Kuramoto-cho, Tokushima, 770, Japan

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The time dependency of stress distribution in the supporting structures under dentures was simulated, under three loading conditions, by visco-elastic finite element stress analysis. In this simulation, viscoelastic material, was used as a model for soft tissue.

The results indicate that the viscous flow of soft tissue and the loading position are factors determining stress intensity in the supporting structures under the denture. The stress intensity in the supporting structures was lowered when the occlusal force shifted towards the palatal side. Simulated results support Pound's lingualized occlusion theory.

Key words: Soft tissue, Finite element stress analysis, Viscoelastic deformation.

INTRODUCTION

In preparing removable dentures, high stress concentration in the supporting structures during mastication must be avoided. High stress concentration causes pain and decubital ulcers under the denture. Bone resorption and permanent deformation in the residual alveolar ridge follow when the ill-fitting denture is used[1)-2)]. It is, then, a fundamental requirement in preparing removable dentures to evaluate stress and strain in the supporting structures.

Many methods have been applied to measure stress and strain distributions in supporting structures. For example, Pezzoli et al[3)]. studied stress distributions in supporting structures under various dentures by reflection photoelasticity. The two-dimensional finite element method has been widely used in prosthodontic fields such as crown, bridge and implantology. However these calculations are based on elastic materials and do not take differences between hard and soft tissue into account[4)]. Stresses in the denture and in the supporting structures were also calculated by Maeda et al[5)]. They pointed out that the loading condition of the occlusal force is an important factor determining stress distribution.

In this study, the viscous flow of soft tissue was considered, and the time dependency of stress distribution in supporting structures was simulated by the visco-elastic finite element method. This analysis was helpful in revealing the effect of viscous flow of the soft tissue on stress distribution in the supporting structures and on the deformation of the denture. The effect of viscoelastic deformation in soft tissue was discussed relating to denture movement.

MATERIALS AND METHODS

Viscoelastic behavior under a unidirectional load is commonly described by the generalized Voigt model as shown in Fig. 1. The basic formulation of the visco-elastic finite element method used in this study was reported in detail by Yamada[6].

Figure 2 shows the calculation of visco-elastic analysis. The outline of the calculating

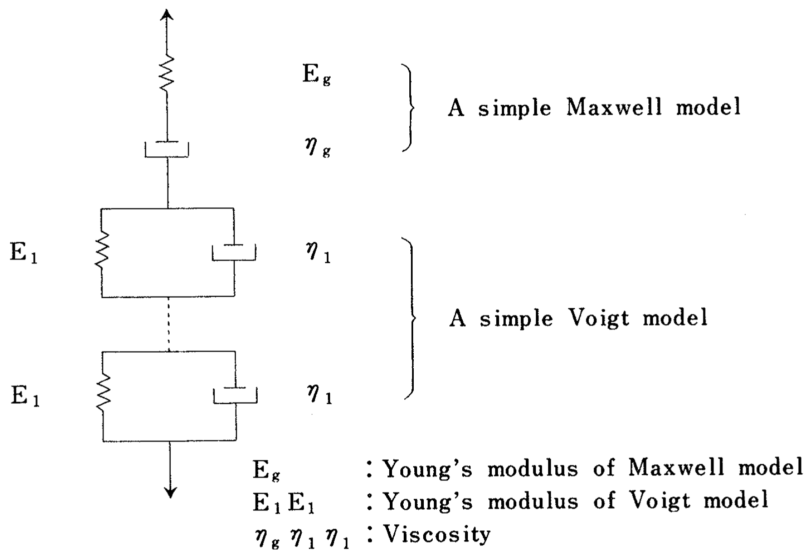

Fig. 1 A generalized Voigt model.

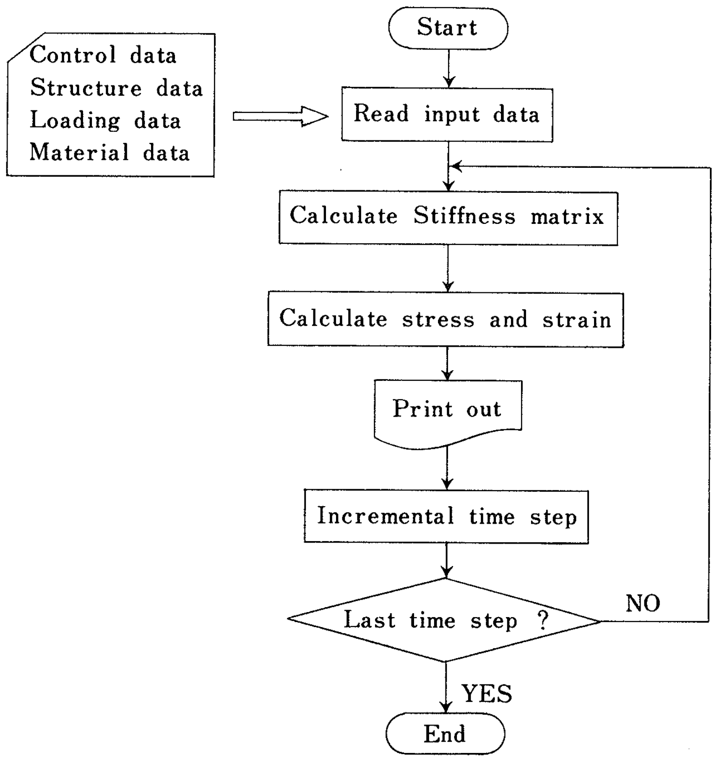

Fig. 2 The flow-chart for computation of a viscoelastic deformation by finite element methods.

procedure follows. The loading time was divided into small time steps, Δt apart. Assuming the increase in the strain during each time step, Δt, was constant, the strain rate was calculated from the creep compliance and viscosity of the material. The incremental stress, $\Delta\sigma(t)$, was calculated for Δt as follows :

$$\{\Delta\sigma(t)\} = [D(t)]\{\Delta\varepsilon(t)\} - \{\Delta\sigma_a\}\ \Delta t \qquad (1)$$

where, $[D(t)]$ is the stiffness matrix calculated from the strain rate for every time step ; $\Delta\varepsilon(t)$ is the incremental strain during Δt ; and $\Delta\sigma_a$ is the apparent incremental stress. Then the initial stress and strain rate, $\Delta\sigma(t)$ was calculated by the elastic calculation[6]. The stress, $\sigma(t)$, was calculated for every time step using the stress calculated from the previous time step and the incremental stress of the stage as follows.

$$\{\sigma(t)\} = \{\sigma(t-1)\} + \{\Delta\sigma(t)\} \qquad (2)$$

Two dimensional plane stress analysis was used in this study. The model composed of materials such as the upper denture base, soft tissue, cortical bone and cancellous bone (Fig. 3)[7], was divided into 269 elements with 158 nodes as shown in Fig. 4. The mechanical properties of the materials used were quoted from reports by Tanaka[8] and Lavernia et al.[9], as shown in Table 1. Viscoelastic deformation was computed under a constant loading force of 49 N at three different loading positions as shown in Fig. 4 : (1) loaded on the buccal side of the residual alveolar crest (point B), (2) loaded on the residual alveolar crest (point C), and (3) loaded on the palatal side of residual alveolar crest (point P).

Transient stress with load was calculated during 3 s by an incremental time step method as shown in Fig. 2. Here the loading time, 3 s, was divided into 0.1 s periods.

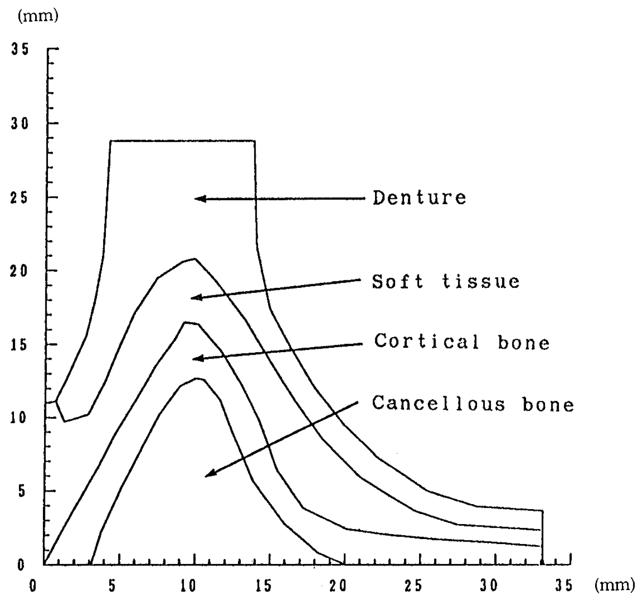

Fig. 3 The simulation model of the upper denture, soft tissue, cortical bone and cancellous bone.

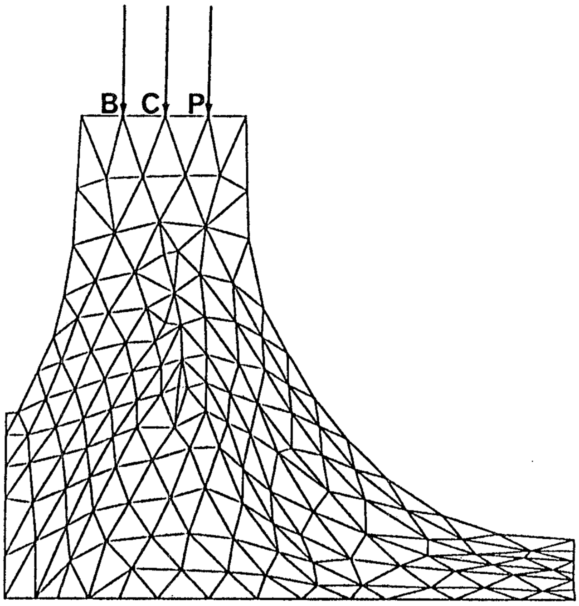

Fig. 4 Mesh pattern and loading conditions. The points B, C and P represent the buccal, central, and palatal loading points, respectively.

Table 1 Mechanical properties

Material	Young's modulus (MPa)	Poisson's ratio
Resin	1960	0.3
Cortical bone	13400	0.3
Cancellous bone	690	0.3

Viscoelastic properties of the soft tissue

Modulus (MPa)	E_1	$= 1.1$
	E_2	$= 1.2$
Viscosity (MPa・s)	η_2	$= 18.0$
	η_3	$= 250.0$

RESULTS

Displacement of denture

Figure 5 shows the results of the displacement of the denture at 0.1 s after loading. The magnification of the displacement is two times as large as the calculated dimensional change. The denture moved vertically and rotated to the buccal side. The horizontal movement was smaller than the vertical translation.

Figure 6 shows denture displacements with the three different loading conditions. Displacement of the denture is represented by the movement of the occlusal table edge at the buccal side at 0.1 s and at 3 s after loading. The denture loaded on B was unsuitable because it was the most unstable of the three calculated models. The displacement in both directions bacame smaller when the loading point moved from B to P.

The displacement of the denture in both directions increased with time for all the loading conditions. The increasing rate of displacement after 3 s was approximately constant and not

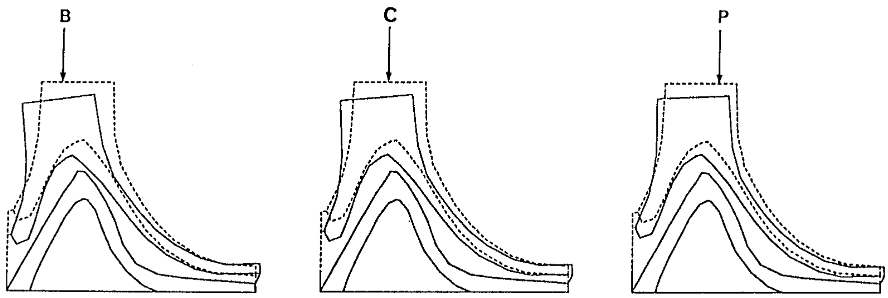

Fig. 5 Displacement of the denture. The displacements are represented at a magnification of two for the calculated results. Solid lines show the initial position of the materials. Broken lines show the displacement at 0.1 s after loading. Points B, C and P represent the buccal, central, and palatal loading points, respectively.

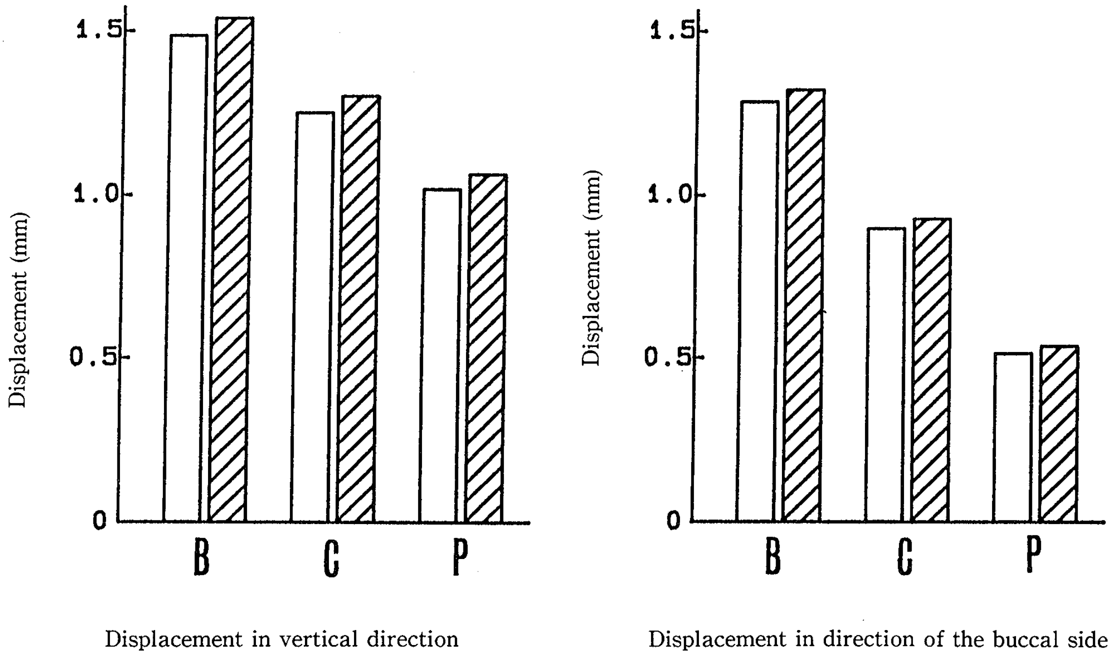

Fig. 6 The displacement of the occlusal table edge at the buccal side (Point A) under different loading conditions. Boxes show the displacement at 0.1 s after loading. Shadowed boxes show the displacement at 3 s after loading. B, C and P represent the buccal, central, and palatal loading points, respectively.

as high. The denture with load on P was the most stable in the mouth because the distance and rate of movement were lowest.

Equivalent stresses in supporting structures

Figure 7 shows equivalent stress distributions in the supporting structures at 0.1 s after loading. The equivalent stress ranged from 40 to 530 kPa in soft tissue. Stress concentrated at the local area under the buccal flange of the denture and above the residual alveolar crest. The stress on the cortical bone ranged from 240 to 3800 kPa. The buccal slope in the residual alveolar ridge acted as a stress concentrator. The stress intensity in this area was the highest in the supporting structures. Equivalent stress in the cancellous bone ranged from 80 to 340

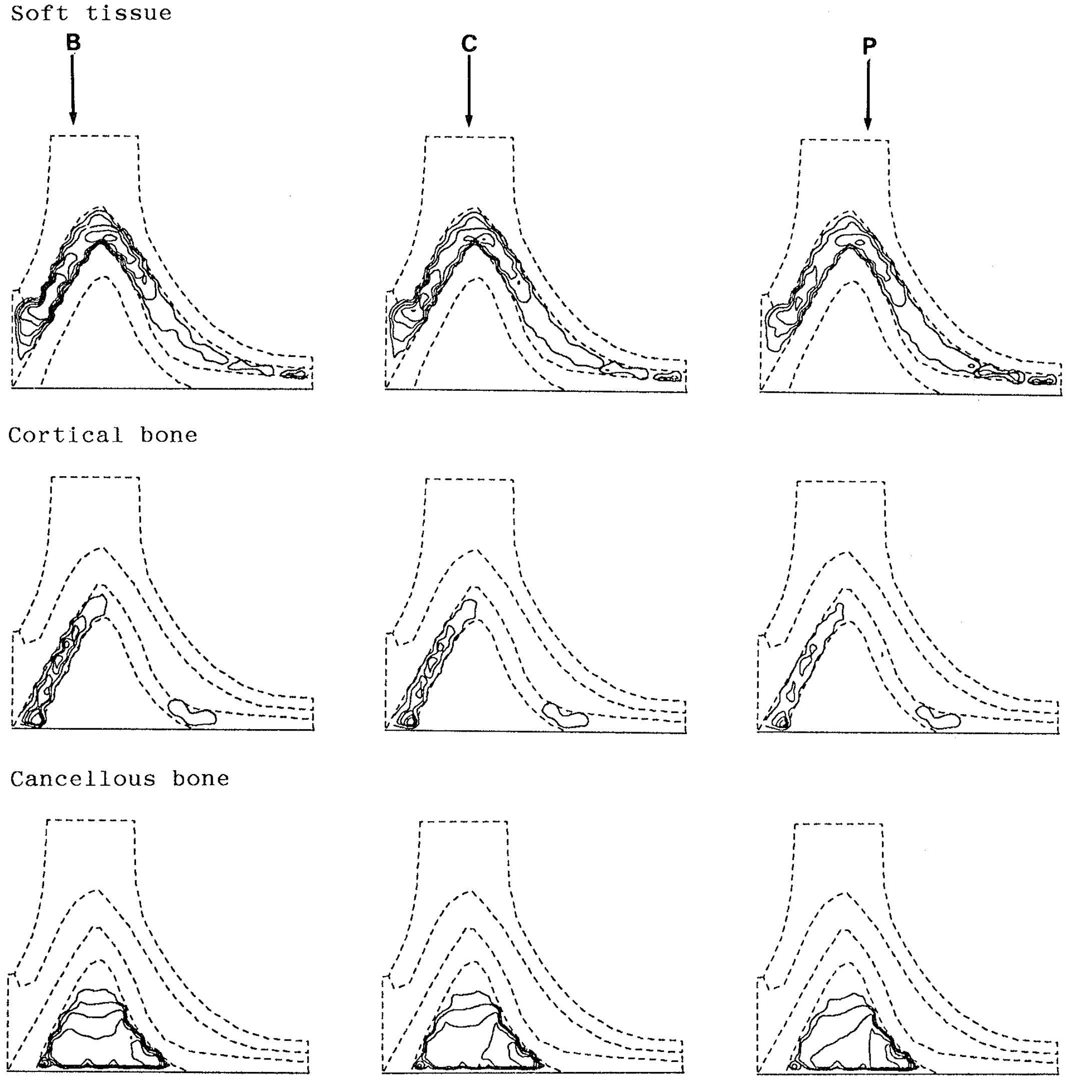

Fig. 7 Stress distributions in supporting structures at 0.1 s after loading under three loading conditions. The points B, C and P represent the buccal, central, and palatal loading points, respectively.

kPa. The palatal slope in the cancellous bone concentrated stress but not as high.

The loading condition affected the stress distribution and intensity. As the loading point shifted from B to P, the stress distribution became uniform.

Figure 8 shows equivalent stress distributions in the supporting structures at 3 s after loading. These stress distributions were similar to those at 0.1 s after loading as shown in Fig. 7. However, the areas of stress concentration, in soft tissue and in cortical bone, expanded to the palatal side and equivalent stress intensities increased with elapse of loading time.

DISCUSSION

One of the mechanical factors determining bone resorption and morphological changes in residual alveolar bone is the stress intensity in the supporting structures[1)2)]. Visco-elastic

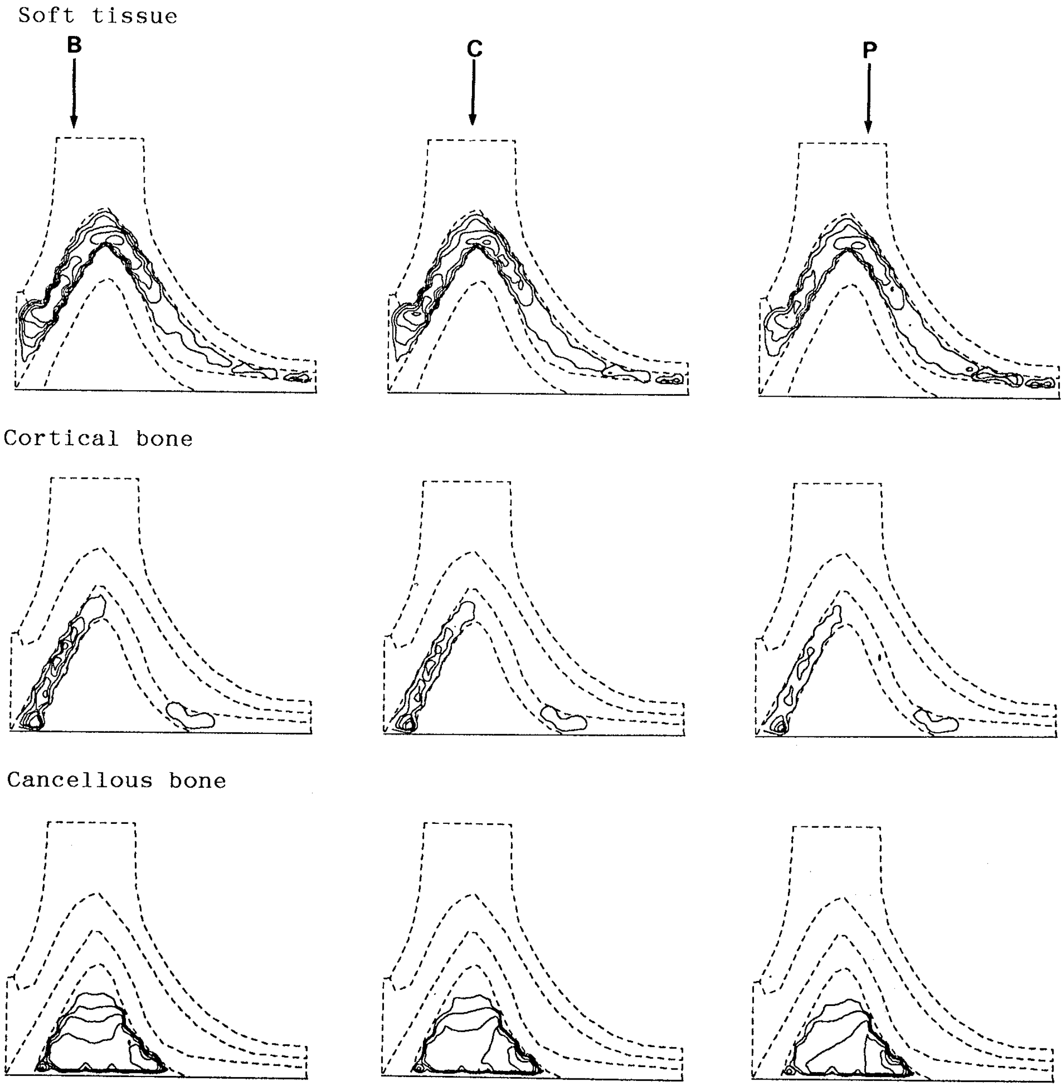

Fig. 8 Stress distributions in supporting structures at 3 s after loading under three loading conditions. B, C and P represent the buccal, central, and palatal loading points, respectively.

finite element stress analysis is a helpful method to investigate the biomechanical problems. The simulations were computed under these four assumptions: (1) deformation of the soft tissue was represented by the Voigt four element model, and constants of the elements were taken from Tanaka[8]; (2) recent studies of chewing force have reported values of 10.6 − 22.0 N[10] and 17.6 − 44.7 N[11], but in this study, external force to the denture was assumed to be 49 N, reportedly the maximal chewing force for denture wearers[11]; (3) simulation was computed for 3 s, because the structures undergo almost no further deformation with longer times; (4) the soft tissue and the denture base were assumed to connect, i. e., slip allowed to each other.

Results of load simulation on the occlusal table showed that the buccal slope of the ridge was the stress concentration area. The stress distributions of these simulations agreed with Maeda and his coworker's observations[5]. The rotation of the denture around a fulcrum on the palatal side of the ridge induced a high stress intensity in the buccal slope of the soft tissue and cortical bone as shown in Fig. 5. The denture was sustained by the buccal slope of the residual alveolar ridge.

The denture moved gradually over the 3 s loading time. Stresses in the alveolar crest and along the palatal side of the ridge increased with time. Tables 2 and 3 show the equivalent stress values in typical elements of the supporting structures shown in Fig. 9. Stresses became uniform with time. These results indicate that the denture was sustained not only by the buccal side but also by the palatal side of the ridge after 3 s. The viscous flow of soft tissue plays an important role in stress distribution, that is, the soft tissue is one of the human protective mechanisms against outside forces.

Functional occulusal forces during chewing and swallowing are related to many factors such as denture design and the material of the denture base. It is hoped that the method developed for this study will prove a useful tool for improving the design of prosthetic appliances and artificial teeth. The direction of external force to the denture is a significant

Table 2 The relationship between the loading position and quivalent stress in each structure at 0.1 s after loading

		B			C			P	
	Bu	Cr	Pa	Bu	Cr	Pa	Bu	Cr	Pa
Soft tissue	630	300	310	540	280	310	440	250	310
Cortical bone	3200	1140	960	2710	1120	1060	2220	1030	1170
Cancellous bone	200	100	230	180	90	220	160	90	220

unit : kPa
B, the loading point was at point B ; C, the loading point was at point C ; P, the loading point was at point P ; Bu, typical elements in the buccal side ; Cr, typical elements in alveolar crest ; Pa, typical elements in the palatal side.

Table 3 The relationship between the loading position and equivalent stress in each structure at 3 s after loading

		B			C			P	
	Bu	Cr	Pa	Bu	Cr	Pa	Bu	Cr	Pa
Soft tissue	630	320	320	540	290	320	440	250	320
Cortical bone	3200	1420	990	2710	1230	1080	2230	1040	1180
Cancellous bone	200	100	230	180	90	220	160	90	220

unit : kPa
B, the loading point was at point B ; C, the loading point was at point C ; P, the loading point was at point P ; Bu, typical elements in the buccal side ; Cr, typical elements in alveolar crest ; Pa, typical elements in the palatal side.

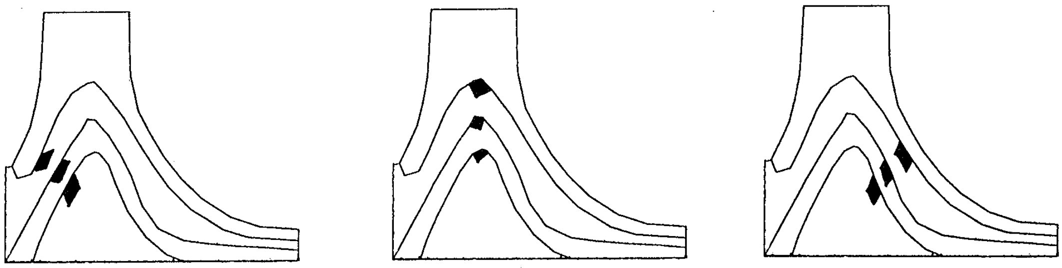

Fig. 9 Position of the typical elements in each structure.

factor in denture movement and stress distribution in the supporting structures.

Figures 5, 7 and 8 indicate that the movement of the denture determined stress distribution in supporting structures. Therefore, large movement of the denture causes high local stress in supporting structures. In general, the limits to enduring stress without pain in the soft tissue ranged from 686 kPa to 1372 kPa[12]. The stress at the buccal slope in soft tissue under loading on B (630 kPa) is the same as the enduring stress (686 kPa) shown in Tables 2 and 3. Comparing the loading condition of P with that of B, differences in stress on the busccal side's soft tissue and cortical bone were about 30 % and the difference in the cancellous bone was about 20 % as shown in Tables 2 and 3. There differences in stress are clinically significant. It is preferable to design a denture on which the functional occlusal force acts like the model presented in loading condition P. For this purpose, the upper artificial posterior teeth can not be shifted towards the palatal side of the alveolar crest, because the lower artificial teeth have to be arranges towards the buccal side of the alveolar crest to keep tongue space. Considering stability of the denture and stress distribution on supporting structures, the loading point should be set towards the palatal side of the alveolar crest. These results agreed with Pound's lingualized occlusion theory[13].

CONCLUSIONS

Transient stress distributions in supporting structures during mastication were simulated by the finite element method. Movement of the denture and stress distributions in supporting structures were calculated under the condition of a vertical load of 49 N.

At 0.1 s after loading, the denture moved vertically and rotated to the buccal side. Stress concentrated at the local area beneath the flange of denture and above the alveolar crest in soft tissue. The moat stressed area in the cortical bone was the buccal slope of the residual alveolar ridge. At 3 s after loading, the displacement of the denture increased and stress concentrated areas extended to the palatal side.

As the loading point moved from the buccal side of the residual alveolar crest to the palatal side, the denture became stable and the stress distribution in the structure became uniform.

These results suggest that viscous flow and loading conditions affect the stress distribution in the supporting structures.

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パラジウム基2元合金の熱膨張係数の温度依存性について

浅岡憲三，桑山則彦
徳島大学歯学部歯科理工学講座

パラジウム基の焼付用合金の基本成分であるPd-Ag, Pd-Cu, Pd-Co 2元合金の熱膨張係数の温度依存性について調べた。その結果，Pd-Ag (Ag＜50%), Pd-Cu (Cu＜30%)合金の室温から600°Cまでの温度での実熱膨張係数が温度の一次式　$\alpha = C_1 + C_2T$　で表されることが明かにされた。また，温度の一次式の定数C_1とC_2が添加元素含有量の一次式で表示できた。すなわち，上記の任意の組成の合金について，任意の温度，温度区間での熱膨張係数が，ここで示された結果を利用して推定できることが明かにされた。

Pd-Cu合金の規則－不規則変態(一次相変態)，Pd-Co合金の磁気変態（二次相変態）と熱膨張係数の関係について調べ，相変態前後の熱膨張係数の特徴が明かにされた。そして，合金の相変態を利用することにより，陶材／合金補綴物中の残留応力が制御でき，相変態による合金の強化と残留応力を利用した陶材の強化を同時に図る陶材／合金システムを作成することの可能性が示唆された。

ハイドロキシアパタイト粉末の物性に及ぼす水溶液中での合成条件の影響

石川邦夫*，今　政幸*，天眞　覚**，桑山則彦*
*徳島大学歯学部歯科理工学講座
**徳島大学歯学部歯科矯正学講座

ハイドロキシアパタイト（HAP）粉末の水溶液中における湿式合成において，HAP粉末の物性に及ぼす合成温度および二酸化炭素の影響を検討した。二酸化炭素が合成系に存在しない場合，合成温度が高くなるとHAP粉末の結晶性がよくなる。一方，合成温度が低い場合，カルシウムとリンの比（Ca/P）が小さいHAP粉末が得られる。FT-IRで測定したリンと水酸基の比（P/OH）はCa/Pが異なるHAP粉末でも一定であり，このことから低い温度での合成ではCa欠損HAPが生成していることがわかった。100°Cで合成したCa欠損のないHAP粉末は1200°Cで3時間安定であったが，40°Cで合成したCa欠損HAP粉末は800°Cで一部リン酸三カルシウムに分解した。

一方，合成中に二酸化炭素が存在するとAタイプおよびBタイプの炭酸含有HAPが生成した。低い温度で合成した場合，炭酸カルシウムも副生した。

粘膜の被圧縮性が義歯床下組織の応力分布に及ぼす影響

河野文昭*，浅岡憲三**，永尾　寛*，松本　直之*
*徳島大学歯学部歯科補綴学第一講座
**徳島大学歯学部歯科理工学講座

義歯床下粘膜が粘弾性体であることを考慮して，有限要素法を拡張した粘弾性解析法を用いて，3種類の異なる荷重条件下での義歯床下組織に生じる応力分布の経時的な変化を計算した。

その結果から，時間経過にともなう粘膜の粘性流動および荷重点は義歯床下組織の応力の分布状態を決定する重要な因子であることが示された。そして，義歯床下組織の応力の不均衡を改善する方法について議論した。義歯床下組織の応力は，咬合力を口蓋方向に変位させることによって最も均等に分散した。このことは，Poundの

提唱する Lingualized Occlusion を支持するものであった。

義歯掘り出しに対する静的模型分割法の確立

右近晋一*，松浦智二*，勝俣辰也*，赤木幸一*，緒方稔泰*，片山隆昭**
*福岡歯科大学歯科補綴学第2講座
**片山歯科医院

重合後の義歯掘り出し時の石膏模型分割法に対し，水和膨張性物質を用いた静的分割法を確立するために本研究は行われた。3種類の分割剤充填孔のデザインを考察し，静的分割法による石膏模型の分割時に，レジン床義歯内に発生する動的歪測定から各デザインの安全性を検討した。

その結果タイプIIのデザインは最も安全であり，かつ効果的であった。動歪の最大値の棄却限界から推定された上限値は，上顎義歯では 2.9×10^{-3} 下顎義歯では 3.4×10^{-3} であった。この値は床用レジンの比例限に相当する critical strain（11.5×10^{-3}）よりはるかに低く1/3程度であり，床用レジンの弾性限度内の挙動であることから破折，変形の危険のない安全な方法とみなすことができる。

ポーセレン－チタン界面への酸化の影響

木村　博，洪　純正，岡崎正之，高橋純造
大阪大学歯学部歯科理工学教室

チタンは耐食性が良く，軽量で，高強度，しかも生体親和性に優れている。一方，通常の金属焼付陶材による修復物は審美性が良く，優れた機械的性質を有するため，歯科界では広く使用されている。本研究では，ポーセレン－チタンの接着強さおよび機械的性質に対する熱処理の影響を調べるため，真空中と大気中で，600 から 1000°C までの熱処理条件を変えて実験を行った。X線回折では，温度の上昇とともに，純チタン表面のα-Ti の相対的ピーク強度が低下したが，TiO_2 のピークは逆に増加した。チタンのビッカース硬さは温度の上昇とともに増加し，特に 900°C 以上の場合には硬さが急増した。熱処理しなかったポーセレン－チタン接合部の引張－せん断強さは最も高い値を示したのに対し，1000°C で熱処理した場合は最も低い値を示した。金属顕微鏡で観察した結果，1000°C で熱処理した場合の界面に最も厚い酸化層が観察された。以上の結果，ポーセレン－チタンの接着強さはチタン酸化膜の増加により低下する傾向があるため，通常の金合金焼付陶材使用時のディギャシングはポーセレン－純チタンの場合には適用できないことがわかった。

メタクリレートとりん脂質及びりん脂質コレステロールリポソーム系との相互作用により誘起されるメタクリレートの NMR ケミカルシフトの変化

藤沢盛一郎，門磨義則*，菰田泰夫*
東京医科歯科大学歯学部
*東京医科歯科大学医用器材研究所

メタクリレート類の生体膜損傷作用のメカニズムを明らかにするため，生体膜モデルとしてりん脂質 (DPPC)