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FINITE ELEMENT ANALYSIS OF MANDIBULAR STRESSES AND DENTURE MOVEMENTS INDUCED BY VARIOUS DENTURE BASE MATERIALS

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I. INTRODUCTION

Maintenance of the supporting tissues in a physiologic condition is a prime requisite when constructing an oral prosthesis. In spite of the best clinical efforts, however, the underlying supporting tissues often undergo degenerative changes. In some cases, the general health and nutritional status of the patient are felt to be the causative factors. In others, these changes are felt to be caused by the unequal distribution of functional forces.28)

In general, the forces applied to a body result in internal stresses. These stresses are modified by the direction and distribution of the reacting forces, and the shape of the body.31) Depending on the capacity of the vital mandible to dissipate and react to occlusal stresses, the stimulation may be beneficial or deterimental. It seems reasonable that the stresses transmitted to the various skeletal components of the masticatory system should be minimized to insure that they do not result in deterimental effects.30)

Among oral prosthesis, the complete denture distributes stresses to the residual alveolar ridge which contribute to the degeneration of the supporting bone.3,7,20) The mandible seems especially susceptible to such degeneration.20,45,46) The reason is that the edentulous mandible is not structurally capable of withstanding forces the dentoalveolar attachment apparatus had once dissipated effectively20,32) and the mandibular bearing surface is reduced considerably compared to the maxillary bearing surface. This factor alone increases the actual force per unit area in the mandible to approximately two or three times compared to that in the maxilla. In long-term longitudinal studies of denture patients, Atwood3) and Tallgren45) substantiated the fact that under complete denture function approximately four times more reduction occurs in the mandible than in the maxilla. This bone resorption compromises the denture bearing area, making it difficult to produce a mandibular denture that possesses qualities of stability and retention. The mechanism of support is further complicated by the fact that complete dentures move in relation to the underlying bone during function. This movement is related to resiliency of the supporting mucosa and submucosa and the inherent instability of the dentures during function. Denture instability has the potential of being traumatic to the supporting tissues since movement of the denture base in any direction on their basal seats can cause tissue change.[51] Dentists have been aware of these problems and have developed numerous philosophies about tooth form, tooth materials, placement of teeth and denture base materials.[19,30] Various studies have been made to determine the efficiency of different tooth forms or occlusal designs, and tooth materials such as the work of Sharry,[39] Trapozzano,[47] Lopuck[30] and others.[42] But there is a little scientific documentation reporting the denture movements and the stresses transmitted to the edentulous mandible by the different types of denture bases. It is suspected that there may exist a significant difference in both the distribution and magnitude of the forces exerted by mandibular complete dentures of various base materials on the residual ridge under occlusal load.

The objective of this investigation was to evaluate the movement and magnitude and mode of distribution of the stress in the complete denture, mucous membrane and supporting bone when various denture base materials were used and different loading schemes were applied.

II. MATERIALS AND METHODS

The finite element method is a well – known procedure for obtaining stresses and displacements in a complex structure. The finite element method, a computerized mathematical technique, involves the idealization of the actual continuum (or model) as an assemblage of a finite number of discrete structural elements interconnected at a finite number of points or nodal points. The finite elements are formed by figuratively cutting the original continuum into a number of appropriately shaped sections and retaining in the elements the properties of the original material.[11]

In this study, a mesio – distal cross – sectional model of an edentulous mandible was developed based on a dried specimen of a human mandible and roentgenograph by use of the softex (Fig. 1).

Four finite element models of a complete denture were made following each denture base material: I) an acrylic resin denture, II) an acrylic resin denture with a 2mm thick resilient liner, III) an acrylic resin denture with a 2mm thick resilient layer interposed between the two layers of the hard denture base, and IV) a 0.5mm thick metal base denture. Each of these was combined with the common part of the mandibular model in order to construct a complete model of each denture base bype (Fig. 2).

The edentulous mandible was simulated having both the cortical and cancellous bones. The buccal shelf area and lower border of the mandible were considered as the cortical bone. A uniform thickness of 2mm of mucous membrane[9,27]

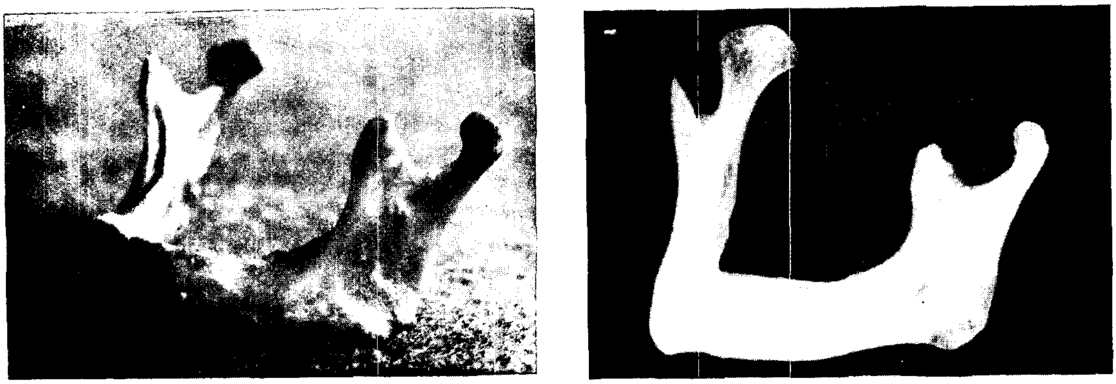

Fig. 1. A dried human mandible and roentgenograph by use of the softex.

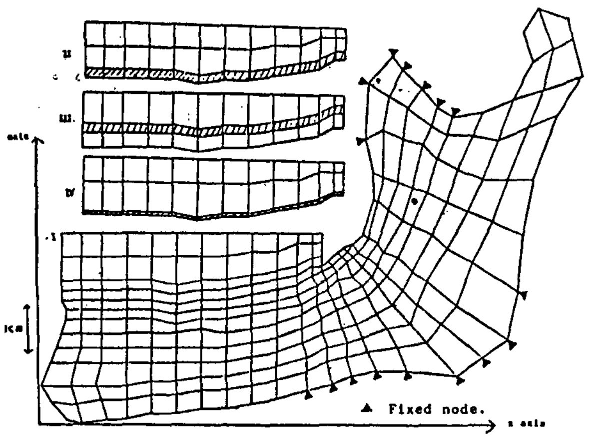

Fig. 2. Finite element models
I. Acrylic resin denture.
II. Acrylic resin denture with a 2mm thick resilient liner.
III. Acrylic resin denture with a 2mm thick resilient layer.
IV. 0.5mm thick metal base (Cr-Co) denture.

was simulated between the denture base and the mandibular model.

Each two-diminsional model was divedid into 231 elements of quadrilaterals with a total of 268 nodal points and each element was assigned the proper materials properties of E, Young's modulus and υ, Poisson's ratio. These constants were obtained from the literature (Table 1) and were assigned to the appropriate regions.

Plane stress elasticity conditions were assumed, and in order to represent the physiological condition as the fixed areas of the mandible under simulated masticatory loading the nine nodes which lie at the mandibular angle region and the seven nodes which are located at the coronoid process at which masseter, temporal and internal pterygoid muscles are attached, were assumed to be fixed so that no deformation was allowed in the horizontal or vertical directions (Fig. 2). Each model was loaded with a magnitude of 10kgs on the first molar region (P_1) and 7kgs on the central incisal region (P_2) in a vertical direction. The force of 10kgs was then applied distributively from the first premolar to the second molar of each model in a vertical direction (P_3).

After these data are specified, the displacements, as well as the stresses can be calculated immediately by a computer program. A widely known, general purpose finite element computer program, the Hinton & Owen's program for microcomputers[17], was used for the analysis of maximum principal stresses, minimum principal stresses, maximum shear stresses and equivalent stresses of each element, as well as the x and y displacement of each nodal point.

Table 1. Mechanical properties assigned to different materials compounds of finite element models.

Material	Modulus of elasticity kg/cm^2	Poisson's ratio	Applicable references
Acryl	24.00 x 10^3	0.29	2)
Resilient material (silicone)	14.06	0.49	2)
Mucous membrane	35.20	0.45	10)
Cancellous bone	7040.80	0.30	8,23)
Cortical bone	14.00 x 10^4	0.30	8,23)
Metal base (chrome-cobalt)	21.10 x 10^5	0.33	10)

III. RESULTS

The computations resulted in values for displacement of each nodal point and stress for each element of model.

1) Displacement

Comparison of the displacement of the denture, the mucous membrane and the alveolar bone is of interest with various denture base materials according to different loading schemes. Fig. 3-14 shows the resulting displacement of each nodal point in the denture, the mucous membrane and the alveolar bone under each condition. Table 2 reveals the amount of displacements of 6 reference points under each condition.

Regarding Fig. 3-6 (P_1), the downward displacements of the posterior edges of the dentures were larger than those of the anterior edges. But, the exceptional upward displacement of the anterior edge of the denture was only slight in P_1-II (0.02mm). The amounts of the total displacements of the posterior edges of the dentures were 0.68mm in P_1-II, 0.64mm in P_1-III, 0.20mm in P_1-IV, and 0.19mm in P_1-I. On the other hand, in Fig. 7-10 (P_2) the downward displacements of the anterior edges and the upward displacements of the posterior edges of the dentures were produced with the rotational movements of the dentures. The amounts of the total displacements of the anterior edges of the dentures were 1.03mm in P_2-II and P_2-III, 0.47mm in P_2-I and 0.46mm P_2-IV and the amounts of the total displacements of the posterior edges of the dentures were 0.39 mm in P_2-II, 0.32mm in P_2-III, 0.17mm in P_2-IV, 0.16mm in P_2-I. In Fig. 11-14 (P_3), the downward displacements appeared at the anterior and posterior edges of the dentures. The amounts of the total displacements of the posterior edges of the dentures, were 0.51mm in P_3-II, 0.48mm in P_3-III, 0.15mm in P_3-I and P_3-IV (Table 2). According to these results, the dentures with the resilient liner and layer showed larger total displacements than any denture without the resilient liner and layer and the amounts of total displacement of the dentures were larger in P_2 than in P_1 and P_3.

Regarding the displacement of the mucous membrane, in the cases of I and IV the amounts of the vertical displacements in the mucous membranes were the same those in the dentures. But in II and III, the amounts of the vertical displacements in the mucous membranes were smaller than those in the dentures (Table 2). These results occurred from the compression of the resilient liner and layer.

The amounts of the horizontal and vertical displacemints of the alveolar bones under each condition were the same in spite of a difference in denture base materials.

2) Stress

Forces are either tensile, compressive, or shearing. The forces of occlusion are complicated and cannot be readily seperated. Therefore, the general procedure in structural design is to evaluate the maximum stresses which exist in a structure and relate these to the inherent strength properties of the materials which compose the structure.[14,31] The maximum principal stresses (the maximum tensile stresses), σ max, the minimum principal stresses (the maximum compressive stresses), σ min as well as the maximum shear stresses, τmax that were examined in each interface area are showed in Tables 3,4 and 5.[18] Considering the principal stress, as seen in Table 3 and 4, the mucous membrane regions were mainly subject to compressive stresses except that the farthest areas at the applied load in P_1 and P_2 were subject to tensile stresses. The amount of maximum principal stresses developed by the different denture base materials under the same loading condition was similar in the mucous membranes and the amount of minimum principal stresses

Table 2. Displacement of 6 reference points under each condition

(Unit: mm)

Reference point (Node No.)	Condition / Displacement	P₁ I	P₁ II	P₁ III	P₁ IV	P₂ I	P₂ II	P₂ III	P₂ IV	P₃ I	P₃ II	P₃ III	P₃ IV
upper anterior edge	X	-0.02	-0.02	-0.04	-0.02	-0.15	-0.28	-0.24	-0.15	-0.04	-0.07	-0.07	-0.05
of denture	Y	-0.06	0.02	-0.02	-0.06	-0.45	-0.99	-1.00	-0.44	-0.14	-0.20	-0.18	-0.15
(1)	Total	0.06	0.03	0.04	0.06	0.47	1.03	1.03	0.46	0.15	0.21	0.19	0.16
upper posterior edge	X	-0.03	-0.03	-0.06	-0.02	-0.14	-0.26	-0.20	-0.14	-0.05	-0.08	-0.09	-0.05
of denture	Y	-0.19	-0.68	-0.64	-0.20	0.08	0.29	0.25	0.09	-0.14	-0.50	-0.47	-0.14
(157)	Total	0.19	0.68	0.64	0.20	0.16	0.39	0.32	0.17	0.15	0.51	0.48	0.15
upper anterior edge	X	-0.05	-0.04	-0.05	-0.05	-0.02	-0.25	-0.03	-0.02	-0.05	-0.09	-0.05	-0.05
of mucous membrane	Y	-0.06	-0.07	-0.06	-0.06	-0.45	-0.48	-0.46	-0.44	-0.14	-0.16	-0.15	-0.15
(4)	Total	0.08	0.08	0.08	0.08	0.45	0.54	0.46	0.44	0.15	0.18	0.16	0.16
upper posterior edge	X	-0.03	0.02	-0.04	-0.04	-0.07	-0.04	-0.07	-0.07	-0.04	0.01	-0.05	-0.05
of mucous membrane	Y	-0.19	-0.11	-0.20	-0.20	0.08	0.04	0.07	0.09	-0.14	-0.08	-0.15	-0.14
(160)	Total	0.19	0.11	0.20	0.20	0.11	0.06	0.10	0.11	0.15	0.09	0.16	0.15
upper anterior edge	X	-0.02	-0.02	-0.02	-0.02	-0.06	-0.06	-0.06	-0.06	-0.03	-0.03	-0.03	-0.03
of alveolar bone	Y	-0.09	-0.09	-0.09	-0.09	-0.24	-0.25	-0.24	-0.24	-0.13	-0.13	-0.13	-0.13
(5)	Total	0.09	0.09	0.09	0.09	0.25	0.26	0.25	0.25	0.13	0.13	0.13	0.13
upper posterior edge	X	0	0	0	0	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
of alveolar bone	Y	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
(161)	Total	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Kinds of denture base
I: Acrylic resin denture.
II: Acrylic resin denture with a 2mm resilient liner.
III: Acrylic resin denture with a 2mm resilient layer interposed.
IV: 0.5mm thick metal base denture.

Loading conditions
P_1 : 10kg on the 1st molar.
P_2 : 7kg on the central incisor.
P_3 : 10kg from the 1st premolar to the 2nd molar.

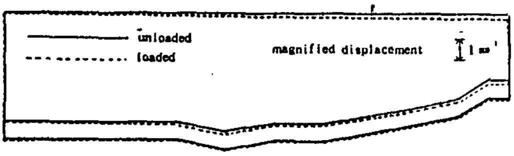

Fig. 3. Displacement of structure with acrylic resin denture (P₁ -I).

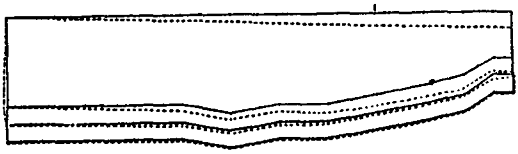

Fig. 4. Displacement of structure with resilient liner (P₁ -II).

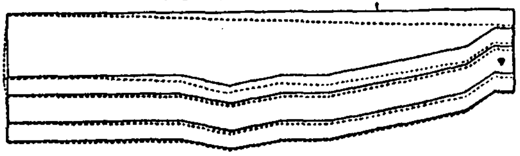

Fig. 5. Displacement of structure with resilient layer (P₁ -III).

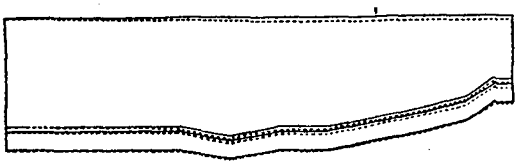

Fig. 6. Displacement of structure with metal base denture (P₁ -IV).

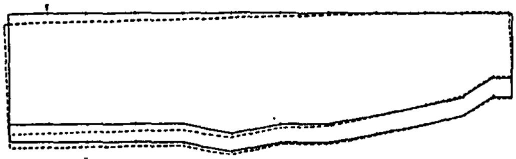

Fig. 7. Displacement of structure with acrylic resin denture (P₂ -I).

Fig. 8. Displacement of structure with resilient liner (P₂ -II)..

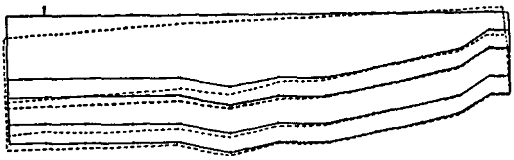

Fig. 9. Displacement of structure with resilent layer (P₂ -III)

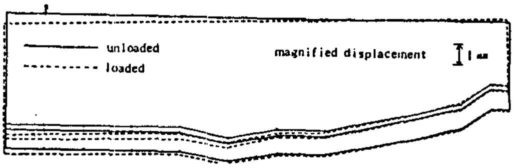

Fig. 10. Displacement of structure with metal base denture (P₂ -IV).

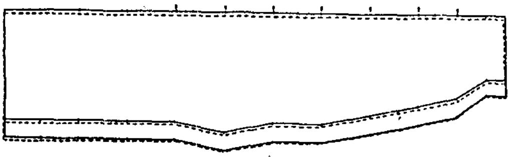

Fig. 11. Displacement of structure with acrylic resin denture (P₃ -I)

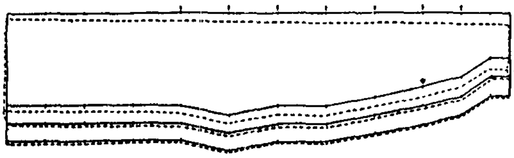

Fig. 12. Displacement of structure with resilient liner (P₃ -II).

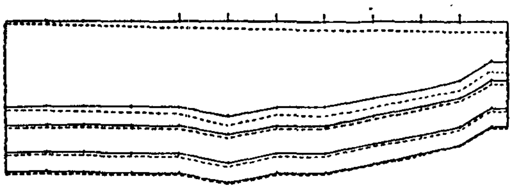

Fig. 13. Displacement of structure with resilient layer (P₃ -III).

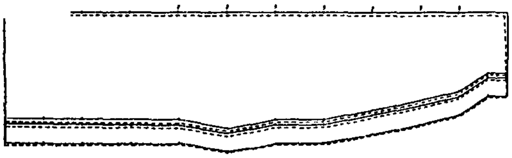

Fig. 14. Displacement of structure metal base denture (P₃ -IV).

was also similar. But the ridge crest regions were mainly subject to tensile stresses considering the maximum principal stress and to compressive stresses considering the minimum principal stress. The amount of maximum principal stresses was slightly higher in dentures with the reselient liner and layer (II, III) than in dentures without the resilient liner and layer (II, IV) in the ridge crest.

The area of greatest maximum principal stress in the ridge crest was on the posterior region of the ridge crest. As seen in Table 5, the amount of maximum shear stresses in the mucous membrane area developed by the different denture base materials under the same loading condition was similar but, strictly speaking, the amount of maximum shear stress in the case of the acrylic resin denture with a resilient liner was slightly higher than in any other denture examined. In addition, the amount of maximum shear stress in the ridge crest region was slightly higher in the dentures without the resilient liner and layer than in the dentures with the resilient liner and layer. Especially, the greatest maximum shear stress was developed in the posterior region of the ridge crest regardless of denture base materials and loading conditions. In overall effect, the metal base denture transmitted slightly less maximum shear stress to the ridge than any other denture examined (Table 5).

The stresses in Table 6 were equivalent stresses which give an indication of the sensitivity of the model to the applied load and are also a measurement of the seriousness of stress at a given point.[34,48)] Therefore, in order to comprehend magnitudes of stress, equivalent stress (ES) was calculated by the following formula:[43,44)]

$ES = \sqrt{\sigma\,\max^2 - \sigma\,\max \cdot \sigma\,\min + \sigma\,\min^2}$. The amounts of equivalent stresses developed by the different denture base materials under the same loading condition were similar in the mucous membrane. But the amounts of equivalent stresses under the same loading condition in the ridge crest were slightly larger in denture with the resilient liner and layer (II, III) than in dentures without the reselient liner and layer (I, IV).

To facilitate presentation and interpretation of equivalent stress, schematic representations of equivalent stress intensity was prepared (Fig. 15-27). The colored patterns reveal the location and intensity of equivalent stress concentration. But stresses with magnitudes of less than 2 kg/cm^2 could not be shown in the figures because of the scale chosen for the stresses. The stress patterns observed within the model with each type and location of applied load showed unique variation as well as some similarities. Considering equivalent stress in the denture (Fig. 15-27), the dentures examined had stress patterns that were localized more at the applied load area and the acrylic resin denture with a 2mm resilient layer (III) had the highest stress concentration (Fig. 18,22 and 26) followed by the acrylic resin denture with a resilient liner and the conventional resin denture in that order. High stresses were encountered in the metal base and were widely distributed throughout the metal base because of the higher physical properties of the metal (Fig. 19,23, and 27). In regard to equivalent stress in the mucous membrane, the pattern of equivalent stresses developed by the different denture base materials under the same loading condition were similar, and regarding equevalent stress in the mandibular bone, the anterior load of the denture base produced greater a stress pattern than any other load scheme because of the long lever arm distance from the fixed point to the loading point. Stresses which occurred at the mandible under the denture were not limited to the denture bearing area but were rather widely distributed. As seen in Fig. 16-27, the posterior region of the ridge crest was highly stressed and high stresses were also encountered to the inferior and posterior border of the mandible due to fixed areas. Comparison of the magnitude and depth of stress with the different denture base materials indicated that the dentures with the resilient liner and layer generated slightly more stress within the ridge than did the acrylic resin denture and metal base denture. In overall effect, the type of denture base material made no great difference on stress distribution of the mandibular ridge (Table 6).

Table 3. Maximum principal stress at selected elements

(Unit: kg/cm²)

Element No.		Condition	P₁				P₂				P₃			
			I	II	III	IV	I	II	III	IV	I	II	III	IV
MUCOUS MEMBRANE	ANTERIOR	4	0.57	0.47	0.52	0.52	-1.90	-0.94	-1.96	-1.85	-0.18	-0.05	-0.24	-0.23
		21	0.26	0.41	0.23	0.23	-1.66	-1.65	-1.71	-1.64	-0.30	-0.23	-0.35	-0.34
		28	-0.03	0.09	-0.05	-0.06	-1.38	-1.47	-.142	-1.39	-0.44	-0.40	-0.46	-0.46
		45	-0.30	-0.24	-0.31	-0.32	-1.09	-1.16	-1.11	-1.12	-0.59	-0.57	-0.59	-0.60
		52	-0.66	-0.54	-0.66	-0.66	-0.69	-0.78	-0.63	-0.70	-0.80	-0.71	-0.78	-0.78
		69	-0.64	-0.68	-0.63	-0.65	-0.69	-0.57	-0.63	-0.73	-0.79	-0.77	-0.76	-0.77
	POSTERIOR	76	-1.02	-0.91	-1.00	-1.01	-0.35	-0.26	-0.28	-0.38	-0.99	-0.89	-0.95	-0.97
		93	-1.09	-1.08	-1.06	-1.08	-0.16	0.04	-0.11	-0.18	-0.98	-0.94	-0.94	-0.96
		100	-1.29	-1.28	-1.26	-1.27	0.35	0.47	0.27	0.23	-1.04	-1.02	-1.01	-1.03
		117	-1.41	-1.36	-1.41	-1.42	0.91	0.98	0.87	0.94	-1.06	-1.04	-1.06	-1.05
		124	-1.11	-1.48	-1.11	-1.11	1.93	1.75	1.78	1.98	-0.67	-1.07	-0.69	-0.68
		141	-1.73	-0.90	-1.82	-1.77	1.83	1.67	1.68	1.98	-1.22	-0.59	-1.31	-1.28
RIDGE CREST	ANTERIOR	5	0.44	0.34	0.38	0.40	1.02	1.74	1.09	1.01	0.24	0.45	0.26	0.25
		20	0.38	0.48	0.37	0.35	0.49	1.68	0.59	0.51	0.32	0.66	0.32	0.30
		29	0.33	0.50	0.34	0.31	0.55	1.47	0.90	0.81	0.37	0.64	0.38	0.35
		44	0.34	0.58	0.36	0.33	0.80	2.32	1.96	1.80	0.61	0.93	0.64	0.60
		53	1.14	1.50	1.17	1.12	4.80	5.52	5.04	4.79	1.99	2.48	2.06	1.98
		68	1.88	2.2 2	1.95	1.87	8.03	8.95	8.34	8.02	3.38	3.88	3.47	3.32
	POSTERIOR	77	3.27	3.70	3.33	3.24	11.08	12.05	11.40	10.05	5.24	5.85	5.35	5.23
		92	5.19	5.69	5.26	5.15	15.75	16.81	16.08	15.74	7.96	8.63	8.06	7.92
		101	8.08	8.72	8.13	8.00	21.22	22.20	21.53	21.21	11.66	12.42	11.75	11.59
		116	16.48	17.71	16.52	16.28	39.44	40.75	39.90	36.47	22.87	24.20	22.98	22.71
		125	16.34	17.73	16.37	16.16	36.78	37.64	37.15	36.91	22.06	23.44	22.17	21.91
		140	18.68	19.58	18.75	18.55	39.93	40.12	40.18	39.90	24.69	25.48	24.81	24.57

A positive sign indicates tensile stress: a negative sign indicates compressive stress.

Table 4. Minimum principal stress at selected elements

(Unit: kg/cm²)

Element No.		Condition	P₁ I	P₁ I	P₁ III	P₁ IV	P₂ I	P₂ II	P₂ III	P₂ IV	P₃ I	P₃ II	P₃ III	P₃ IV
MUCOUS MEMBRANE	ANTERIOR	4	0.08	-0.06	0.06	0.06	-4.39	-4.29	-4.49	-4.26	-0.54	-0.74	-0.64	-0.61
		21	-0.17	-0.25	-0.20	-0.18	-3.87	-3.96	-3.95	-3.79	-0.79	-0.88	-0.86	-0.83
		28	-0.52	-0.60	-0.53	-0.52	-3.26	-3.40	-3.32	-3.25	-1.08	-1.15	-1.11	-1.09
		45	-0.95	-1.10	-0.96	-0.94	-2.63	-2.77	-.264	-2.67	-1.40	-1.40	-1.39	-1.37
		52	-1.58	-1.59	-1.55	-1.54	-1.92	-2.02	-1.87	-2.01	-1.80	-1.78	-1.74	-1.74
		69	-1.82	-1.90	-1.79	-1.79	-1.66	-1.53	-1.55	-1.75	-1.97	-1.94	-1.88	-1.90
	POSTERIOR	76	-2.45	-2.47	-2.37	-2.39	-0.99	-0.91	-0.86	-1.07	-2.31	-2.26	-2.21	-2.24
		93	-2.81	-2.82	-2.73	-2.75	-0.47	-0.39	-0.37	-0.54	-2.47	-2.42	-2.39	-2.42
		100	-3.24	-3.34	-3.18	-3.21	0.09	0.20	0.12	0.09	-2.65	-2.69	-2.62	-2.64
		117	-3.53	-3.51	-3.51	-3.56	0.37	0.44	0.35	0.41	-2.72	-2.69	-2.77	-2.77
		124	-3.66	-4.20	-3.76	-3.74	0.87	0.68	0.81	0.90	-2.61	-3.09	-2.72	-2.68
		141	-3.91	-3.39	-4.11	-4.07	0.70	0.62	0.64	0.79	-2.82	-2.44	-3.02	-2.97
RIDGE CREST	ANTERIOR	5	-0.03	-0.02	-0.03	-0.03	-5.01	-5.31	-5.18	-4.89	-0.70	-0.95	-0.83	-0.79
		20	-0.14	-0.18	-0.15	-0.15	-3.65	-3.50	-3.74	-3.58	-0.77	-0.82	-0.84	-0.81
		29	-0.47	-0.51	-0.59	-0.48	-3.27	-3.38	-3.32	-3.25	-1.05	-1.10	-1.09	-1.07
		44	-1.05	-1.11	-1.05	-1.04	-2.72	-2.87	-2.73	-2.76	-1.50	-1.54	-1.48	-1.47
		53	-1.33	-1.31	-1.31	-1.31	-1.96	-2.01	-1.91	-2.04	-1.62	-1.56	-1.57	-1.58
		68	-1.83	-1.84	-1.79	-1.79	-1.52	-1.42	-1.42	-1.61	-1.95	-1.88	-1.87	-1.89
	POSTERIOR	77	-2.18	-2.17	-2.12	-2.13	-1.06	-0.63	-0.93	-1.15	-2.13	-2.05	-2.04	-2.07
		92	-3.06	-3.04	-2.75	-3.00	-0.79	-0.50	-1.03	-0.84	-2.75	-2.68	-2.67	-2.70
		101	-1.34	-1.30	-1.28	-1.31	1.51	1.71	1.58	1.48	-0.77	-0.70	-0.72	-0.75
		116	-4.33	-4.38	-4.28	-4.31	-0.57	-0.49	-0.70	-0.70	-3.70	-3.73	-3.69	-3.70
		125	-3.33	-3.52	-3.44	-3.43	3.29	3.08	3.14	3.38	-1.85	-2.11	-1.98	-1.94
		140	-1.95	-2.04	-2.09	-2.06	4.64	4.25	4.52	4.72	-0.34	-0.52	-0.48	-0.44

A positive sign indicates tensile stress: a negative sign indicates compressive stress.

Table 5. Maximum shear stress at selected elements

(Unit: kg/cm²)

Element No.		Condition	P_1				P_2				P_3			
			I	II	III	IV	I	II	III	IV	I	II	III	IV
MUCOUS MEMBRANE	ANTERIOR	4	0.50	0.53	0.47	0.46	2.50	3.35	2.53	2.41	0.37	-0.70	0.40	0.38
		21	0.44	0.66	0.43	0.41	2.21	2.31	2.24	2.15	0.49	-0.65	0.51	0.49
		28	0.48	0.69	0.48	0.46	1.88	1.94	1.90	1.86	0.63	-0.75	0.64	0.62
		45	0.65	0.87	0.65	0.63	1.54	1.62	1.54	1.56	0.80	-0.91	0.79	0.78
		52	0.87	1.05	0.90	0.89	1.27	1.24	1.24	1.32	1.00	-1.05	0.97	0.97
	POSTERIOR	69	1.18	1.22	1.15	1.14	0.97	0.96	0.92	1.03	1.18	-1.17	1.13	1.14
		76	1.42	1.55	1.38	1.38	0.63	0.65	0.58	0.70	1.32	-1.38	1.26	1.27
		93	1.72	1.75	1.67	1.68	0.31	0.37	0.27	0.36	1.48	-1.48	1.37	1.46
		100	1.96	2.07	1.93	1.94	0.17	0.28	0.15	0.14	1.61	-1.67	1.61	1.61
		117	2.12	2.15	2.14	2.14	0.55	0.54	0.52	0.54	1.67	1.66	1.71	1.70
		124	2.56	2.72	2.64	2.63	1.06	1.07	0.97	1.09	1.94	2.02	2.03	2.01
		141	2.18	2.49	2.29	2.27	1.13	1.01	1.04	1.19	1.61	1.85	1.72	1.69
RIDGE CREST	ANTERIOR	5	0.47	0.36	0.40	0.43	6.03	7.04	6.27	5.89	0.94	-1.39	1.09	1.03
		20	0.52	0.67	0.53	0.50	4.15	5.18	4.32	4.09	1.09	-1.48	1.16	1.01
		29	0.81	1.04	0.83	0.79	3.32	4.84	4.22	4.05	1.42	-1.74	1.46	1.42
		44	1.39	1.70	1.41	1.37	4.53	5.19	4.69	4.56	2.08	-2.46	2.12	2.07
		53	2.46	2.80	2.48	2.43	6.76	7.53	5.95	6.82	3.60	4.04	3.62	3.55
	POSTERIOR	68	3.17	4.06	3.73	3.67	9.56	10.37	9.76	9.63	5.31	5.76	5.33	5.25
		77	5.45	5.86	5.46	5.38	12.14	12.98	12.34	12.20	7.37	7.90	7.39	7.30
		92	8.24	8.73	8.23	8.15	16.54	17.39	16.77	16.58	10.76	11.30	10.73	10.62
		101	9.42	10.02	9.41	9.31	19.71	20.49	19.95	18.74	12.43	13.10	12.47	12.34
		116	20.80	22.09	20.80	20.60	40.12	41.25	40.59	40.17	26.57	27.93	26.65	26.41
		125	19.66	21.25	19.81	19.59	33.49	34.56	34.00	33.43	23.91	25.55	24.13	23.85
		140	20.62	21.62	20.84	20.61	35.28	35.87	35.66	35.18	25.03	26.00	25.29	25.01

(This data is $\sigma_1 - \sigma_2$ · Maximum shear stress = $\frac{\sigma_1 - \sigma_2}{2}$)

A negative or positive sign *indicates direction.*

Table 6. Equivalent stress at selected elements

(Unit: kg/cm^2)

Element No.		Condition	P_1				P_2				P_3			
			I	II	III	IV	I	II	III	IV	I	II	II	IV
MUCOUS MEMBRANE	ANTERIOR	4	0.57	0.55	0.53	0.53	4.39	4.29	4.49	4.26	0.54	0.75	0.64	0.61
		21	0.44	0.65	0.42	0.41	3.87	3.96	3.95	3.79	0.79	0.88	1.11	0.83
		28	0.54	0.70	0.55	0.53	3.26	3.40	3.32	3.25	1.08	1.15	1.11	1.09
		45	0.95	1.10	0.96	0.94	2.63	2.77	2.63	2.67	1.40	1.49	1.39	1.37
		52	1.58	1.59	1.55	1.54	1.92	2.02	1.88	2.01	1.80	1.78	1.74	1.74
		69	1.82	1.90	1.79	1.79	1.66	1.53	1.55	1.75	1.97	1.94	1.88	1.90
	POSTERIOR	76	2.45	2.47	2.37	2.39	0.99	0.91	0.86	1.07	2.31	2.26	2.21	2.24
		93	2.81	2.82	2.73	2.75	0.47	0.39	0.37	0.54	2.47	2.42	2.39	2.42
		100	3.24	3.34	3.18	3.21	0.26	0.47	0.27	0.25	2.65	2.69	2.62	2.64
		117	3.53	3.51	3.55	3.56	0.91	0.98	0.87	0.94	2.72	2.69	2.77	2.77
		124	3.66	4.20	4.68	3.74	1.93	1.75	1.78	1.99	2.61	3.09	2.72	2.68
		141	3.91	3.39	4.11	4.07	1.83	1.67	1.68	1.98	2.82	2.46	3.02	2.97
		Mean	2.13	2.19	2.20	2.12	2.01	2.01	1.97	2.04	1.93	1.97	1.97	1.94
RIDGE CREST	ANTERIOR	5	0.49	0.37	0.42	0.44	6.03	7.04	6.30	5.89	0.94	1.39	1.09	1.03
		20	0.51	0.67	0.53	0.50	4.15	5.18	4.321	4.09	1.09	1.48	1.46	1.10
		29	0.81	1.03	0.82	0.79	4.07	4.84	4.22	4.05	1.42	1.74	1.46	1.42
		44	1.39	1.70	1.41	1.37	4.53	5.19	4.69	4.56	2.10	2.46	2.39	2.07
		53	2.46	2.80	2.48	2.43	6.76	7.53	6.93	6.82	3.60	4.04	3.62	3.55
		68	3.71	4.06	3.73	3.67	9.56	10.37	9.76	9.63	5.31	5.76	5.34	5.25
	POSTERIOR	77	5.45	5.86	5.46	5.38	12.14	12.98	12.34	12.20	7.37	7.90	7.39	7.30
		92	8.24	8.73	8.22	8.15	16.68	17.59	16.94	16.70	10.70	11.30	10.73	10.62
		101	9.42	10.04	9.41	9.31	21.22	22.20	21.53	21.21	12.64	13.39	12.70	12.56
		116	20.80	11.09	20.80	20.60	40.52	41.64	40.93	40.56	26.57	27.93	26.67	26.41
		125	19.66	21.25	19.81	19.59	37.64	37.64	37.15	36.81	23.91	25.55	24.28	23.85
		140	20.62	21.63	20.84	20.61	41.24	41.31	41.45	41.23	25.90	26.84	26.79	25.83
		Mean	7.80	8.35	7.83	7.74	17.05	17.79	17.21	16.98	10.13	10.82	10.33	10.08

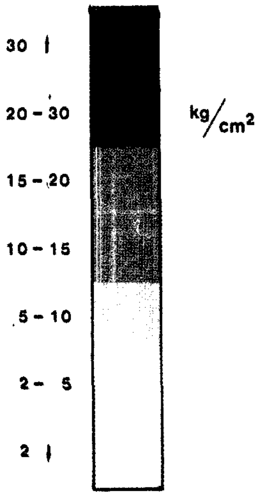

Fig. 15. Range of equivalent stress magnitudes depicted in Fig. 16-27.

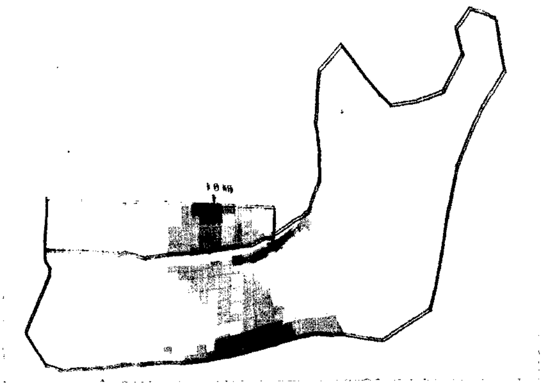

Fig. 16. Equivalent stress of structure with acrylic resin denture (P_1-I).

Fig. 17. Equivalent stress of structure with resilent liner (P_1-II).

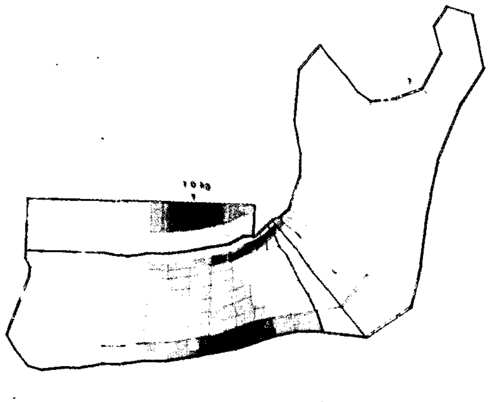

Fig. 18. Equivalent stress of structure with resilient layer (P_1-III).

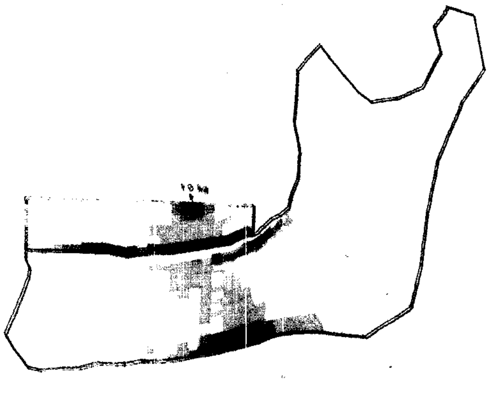

Fig. 19. Equivalent stress of structure with metal base (P_1-IV).

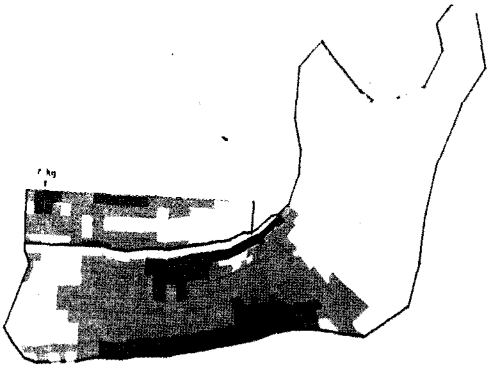

Fig. 20. Equivalent stress of structure with acrylic resin denture (P_2-I).

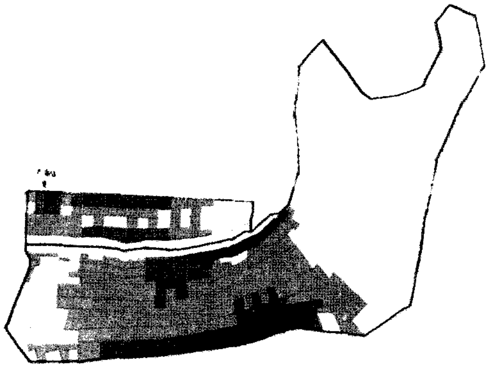

Fig. 21. Equivalent stress of structure with resilient liner (P_2-II).

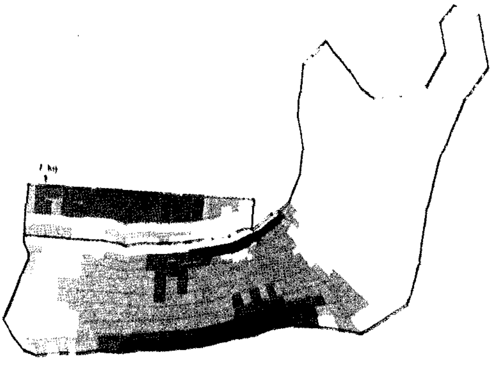

Fig. 22. Equivalent stress of structure with resilient layer (P_2-III).

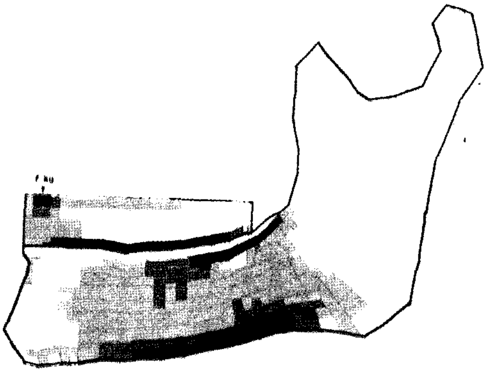

Fig. 23. Equivalent stress of structure with metal base (P_2-IV).

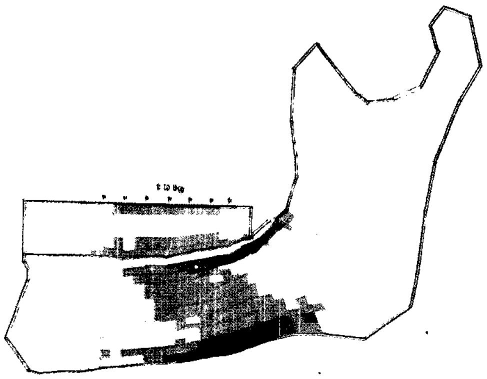

Fig. 24. Equivalent stress of structure with acrylic resin denture (P_3-I).

Fig. 25. Equivalent stress of structure with resilient liner (P_3-II).

Fig. 26. Equivalent stress of structure with resilient layer (P_3-III).

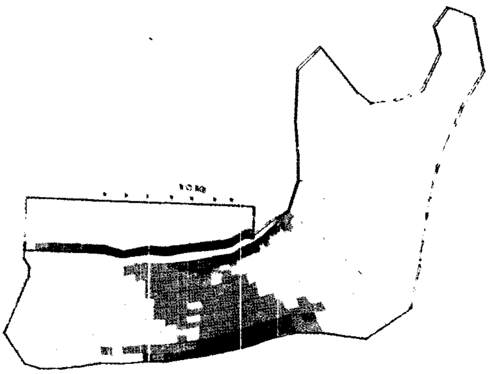

Fig. 27. Equivalent stress of structure with metal base (P_3-IV).

IV. DISCUSSION

Because of the complex geometry and physiology of dental and oral structures, most biomechanical studies in dentistry were performed in vitro. Since this in vitro experiment cannot at present duplicate exactly the in vivo conditions, the absolute values obtained do not exactly correspond to the in vivo situation.[18)]

Recently, two engineering methods have been used for analyzing the stresses in the dental models[15,37)]:

1) the photoelastic method and
2) the finite element method.

The photoelastic method has the advantage of providing an overall picture of the stress (magnitute and direction) in the body, thereby allowing one to make geometrical modifications when deemed necessary.[1,19)] But with the photoelastic materials that are eventually available, it is virtually impossible to proportion the model stiffness in the correct manner.[48,50)] On the other hand, the finite element method, an advanced computer technique of structural stress analysis developed in engineering mechanics, is a numerical analysis method by which the complete components of the stresses, as well as the x and y displacements, can be obtained. This finite element method permits an approximation of both the shape of the objective system and the properties of its constituent tissues.[10,21,47)] Ledley[29)] reported that this theoretical stress analysis eliminated the necessity for attempting the extremely difficult task of making direct experimental measurements. It is, therefore, expected that the finite element method may be capable of systematically and quantitatively analyzing biomechanical tissue response.[29)]

Furthermore, using the finite element approach, the proper material properties can be added. Such an addition allows the model to approximate more closely an actual structure in comparison with the photoelastic approach. Therefore, for the purpose of simplicity, convinience and camparison this study was performed by use of a two dimensional finite element analysis. It was possible to proportionally calculate deflections and stresses under any magnitude of load because this stress analysis was made within the proportional limit.[43)] Therefore, it was suggested that the results obtained be qualitatively reviewed and that a quantitative review be avoided.

1) Displacement

In edentulous mouths, there is much more variation in soft tissue thickness than in dentated mouths and the tissue in elderly persons is thin and takes many hours to recover from the effect of moderate mechanical force.[26,27)] Thicker tissues produce proportionally more change in thickness than do thinner tissues when the same force per unit area is applied.[26)] In this study, the thickness of the simulated mucous membrane was uniformly made to a depth of 2mm according to the findings of kydd and Daly.[27)]

For determining the most general displacement of the denture, both rotation and translation must be observed. Arstad[2)] and Smith, et. al[40)] reported that more denture movement might be expected when the ridge conditions are less favorable and Parker[33)] stated that a tendency to rotational movement of the opposite side of the denture would be countered by greater retention of the denture base by virtue of its closer adaptation to the mucosal seat. This study was performed within the average mandibular model and the assumption was made that before loading there was complete contact between the denture and the residual ridge all along the dividing surface. Results from this assumption can be used to compare various denture base materials for stresses and displacement. In this study, the denture bases under different loading schemes showed not merely simple sinking, but also a rotatory phenomenon, the degree of which varied according to the measured point. The dentures with the resilient liner and layer showed more total displacement than did any denture without the resilient liner and layer (Table 2). Aydinlik and Akay$^{4)}$ reported that with a resilient layer, vertical displacements were almost uniform along the base of the denture but without a resilient layer, vertical displacements increased toward the point of application of the load with a steep gradient. But the results of this study were contrary to their results and rather showed more rotatory movement in the dentures with the resilient liner and layer than in the denture without the resilient liner and layer (Fig. 3-14). The resilient liner and layer could effectively increase the thickness of the oral tissue by serving as an analog of the mucoperiosteum with its relatively low elastic modulus, so *that the overall movement of the denture* was increased.

Bell$^{5)}$ reported that when the adapatness was poor, a resilient denture liner often caused greater tissue injury than a denture with a hard basal surface because of more friction and severe mobility of a denture with a resilient liner. In this study there was a compression of the resilient liner and layer toward the tissue in addition to the displacement of the soft tissue (Fig. 4,5,8,9,12, 13). Parker$^{33)}$ stated that some deformation of the resilient liner and layer occurred before the hard base moved gingivally. This permitted the occlusal part of the bases to move in the vertical and horizontal directions.

Table 2 and Fig. 3-14 show that the metal base denture and the conventional resin denture induced less displacements in the model than did the denture with the resilient liner and layer. It may be concluded that the metal base denture and the conventional resin denture were more stable than the dentures with the resilient liner and layer but the dentures with resilient material seemed to have the "shock absorber effect" during mastication as the compression of the resilient material and an increase in denture movement occurred.

2) Stress

In complete dentures improved comfort and reduced transfer of functional and static stresses to the underlying bone present a strong argument for the use of various denture base materials.$^{16)}$ In a theoretical and laboratory analysis Koivumaa$^{24)}$ found that flexibility in the denture base caused the strain from the masticatory force to be borne by a limited part of the ridge close to the point of application of load, and that the pressure, therefore, was not evenly distributed over all the tissues covered by the denture. Lambrecht and Kydd$^{28)}$ showed that even the hard denture base materials were not quite as rigid as the prosthodontists might wish them to be. Therefore Sauer$^{38)}$ suggested that metal base dentures are more successful in resisting deformation (change in shape) and that these bases increase the rigidity of the denture and thereby reduce the destructive torsional and shear forces. However, Parker$^{33)}$ stated that the liner and layer of resilient material can absorb some of the kinetic energy imparted during function and serve to distribute more widely the load free of shearing stress to the underlying tissue. He further stated that the forces of mastication are chiefly impact forces. The energy delivered at impact is the energy of motion, or kinetic energy, and it is proportional to the mass (M) and the square of the velocity of motion (V); that is, $(K = 1/2\ MV^2)$.

Starke$^{41)}$ and Aydinlik$^{4)}$ observed that the resilient liner acts to reduce and evenly distributing stress to the residual ridge, and Ortamn$^{32)}$ reported that the "shock absorber effect" of the resilient material during mastication is sound because elastic or resilient materials will absorb the kinetic energy of mastication by deformation and heat production and it will also relieve by delaying the static pressure up to the point when the elastic limit of the resilient material is reached. But, in addition to kinetic energy acting on the base during mastication, a static traumatic force is also present during clenching, bruxing, after contact during swallowing, and during pressure seating of the dentures. Under these static forces, the resilient liner and layer would defeat the effort to stabilize the denture base and would increase the force to the basal tissue because the bulk of the rigid base material must be reduced to allow space for the resilient liner and layer which permits the denture to deform and fracture more easily.

As shown in the results of this study, under a static loading condition it was not found that pressure was reduced or distributed more widely over the ridge under the denture base with resilient materials (Fig. 16-27). In fact the dentures with the resilient liner and layer generated slightly more equivalent and maximum shear stresses within the ridge than did the acrylic denture and metal base denture (Tables 5,6). These results were in accordance with observations by Ortman.[32) Douglas[13) suggested that the application of a resilient liner does not reduce the overall masticatory load on the denture bearing area. However, because of its resiliency, it equlibrates the load and is likely to reduce the incidence of point pressures, and traumatic ulceration. This is at least the rationale for its use. Regarding Fig. 19,23 and 27, higher stresses were encountered in the metal base of the model. The reason seemed to be due to the higher physical properties of the metal. As shown in Tables 3,5, and 6, the metal base seemed to be especially effective in transmitting occlusal force from the denture into the ridge of the model. These findings were in accordance with observations by Koivumaa[24), Sauer[38), Korean and Craig[25), and Doezema[12) who mentioned that the metal base mandibular complete denture induced stresses more evenly in the mandible than an acrylic resin base mandibular complete denture.

Without regard to base materials and loading schemes, high equivalent stresses were concentrated in the posterior region of the ridge crest and at the inferior and posterior border of the mandible (Fig. 16-27). The reason for this result seems to be due to the structural properties of bone having thick cortical plates and fixed areas in this finite element method. Koivumaa[24) demonstrated when force is exerted on an object, the distribution is not uniform. The distribution is dependent on (1) the force: surface area ratio, (2) the distance between the point of action of the force and the fixed area, and (3) the elastic properties of the material. But most investigators have not considered the physiologic fixed area of the mandible in mandibular stress analysis. Therefore, the results of experiments on mandibular stress and displacement could be different due to the difference of the fixed areas under loading. In this study, the mandibular angle region and the coronoid process region at which masseter, temporal and internal pterygoid muscles are attached, were assumed to be fixed and bending torque and compression could be observed. The equivalent stresses which occurred at the mandible under the denture were not concentrated in the denture bearing area but were rather widely distributed and the vertical load on the central incisal region produced higher equivalent stress in the mandibular model than any other loading scheme because of the long lever arm distance from the fixed point to the loading point.

As a conclusion, it is generally thought that the metal base denture was more effective in transmitting occlusal force from the denture into the mandible. The resilient liner and layer can be applied to as nearly a rigid denture base as possible without materially decreasing its rigidity in order to prevent fracture and deformation of the thin denture base due to the space occupied by the resilient material. The resilient liner and layer can substitute for the lost resiliency of the mucosal covering in resorbed residual ridges with thin mucosa and sharp bone prominences to prevent an increase in denture movement and to obtain the shock absorber effect.

This finite element method seems to be very useful and effective for physical research in dentistry, and should be considered in complex conditions. But, because of limitations of the two-dimensional model used, the stress analysis and the displacements obtained can only be discussed on a comparative basis. It is imperative that further investigation should be undertaken through the three dimentional finite element method.

V. CONCLUSIONS

This study was to analyze the displacement and the magnitude and mode of distribution of the stresses in the lower complete denture, the mucous membrane and the mandibular bone according to different loading schemes when various denture base materials, I) conventional acrylic resin denture, II) acrylic resin denture with a 2mm resilient liner, III) acrylic resin denture with a 2mm resilient layer interposed and IV) 0.5mm metal base denture, were used. For this study, the two-dimensional finite element method was used. In order to represent physiological condition as the fixed areas of the mandible under loading schemes the nine nodes which lie at the mandibular angle region, and the seven nodes which are located at the coronoid process, at which masseter, temporal and internal pterygoid muscle are attached were assumed to be fixed so that no deformation was allowed in the horizontal or vertical direction.

The results were as follows.

1. When the testing loads were given to the selected points between the anterior and posterior occlusal table of the denture, the denture showed the rotatory phenomenon, as well as sinking and acrylic resin dentures with the resilient liner and layer showed larger displacement than any denture without the resilient liner and layer.
2. Considering the principal stress, the mucous membrane regions were mainly subject to compressive stresses. But the ridge crest regions were subject to tensile and compressive stresses.
3. The acrylic resin denture with a resilient layer interposed had the highest equivalent stress concentration in the denture followed by the acrylic resin denture with a resilient liner and the conventional resin denture in that order and high equivalent stresses were distributed throughout the metal base.
4. The amounts and distribution patterns of equivalent stresses according to denture base materials under the same loading condition were similar in the mucous membrane.
5. The equivalent stresses which occurred at the mandible under the denture were not concentrated in the denture bearing area but were rather widely distributed and high equivalent stresses were encountered in the posterior region of the ridge crest and the inferior and posterior border region of the mandible.
6. The vertical load on the central incisal region produced higher equivalent stress in the mandible than any other load because of the long lever arm distance from the fixed point to the loading point.
7. Differences in denture base material had no great effect on stress distribution in the mandible. But a metal base seemed to be effective in transmitting occlusal stress from the denture into the mandible.

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국문요지

의치상 재료에 따른 하악응력 및 의치의 변위에 관한 유한요소법적 분석

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의치상 재료 종류에 따라 의치, 점막 및 하악골에 발생되는 변위 및 응력을 연구하기 위하여 컴퓨터를 이용한 수치적 해석인 2차원 유한 요소법을 이용하였다. 2차원 유한 요소 모형으로선 표준 크기의 하악골 및 의치를 고려하여 231개의 사변형 요소 및 268개의 절점으로 분할한 후 각 구성 성분의 물리적 성질인 탄성률 및 프와송비를 대입시켰다. 사용된 의치로서는 일반 합성수지의치, 2㎜후경의 탄성재를 의치상 하부에 이장한 합성수지의치, 2㎜후경의 탄성재를 치아와 의치상 중앙에 삽입한 합성수지의치 및 0.5㎜후경의 금속상의치의 4종류였으며, 하중시에 하악의 고정 부위로선 생체와 동일 조건을 부여하기 위하여 교근, 내측익돌근, 측두근등의 하악 폐구근이 부착되는 하악각 부위 및 하악 근돌기 부위의 16절점을 고정점으로 하였다. 하중 조건으로선 하악 제1대구치의 일점에 10㎏의 수직 집중하중, 하악 중절치의 일점에 7㎏의 수직 집중하중 및 하악 제1소구치로 부터 하악 제2대구치까지의 교합면에 10㎏의 수직 분산하중을 부여하여 분석한 결과는 다음과 같다.

1. 하중이 의치 교합면위의 가해진 부위에 따라 다양한 의치 회전 및 강하 현상을 보였으며, 탄성재를 이장 및 삽입한 합성 수지 의치의 변위가 일반 합성수지의치 및 금속상 의치의 변위보다 더 컸다.
2. 주응력을 고려할때 점막 부위에는 주로 압축 응력이 작용하였으며 치조제 부위는 압축응력과 인장 응력이 함께 작용하였다.
3. 탄성재를 삽입한 합성수지의치에 최고 등가 응력이 집중되었으며 그 다음은 탄성재를 이장한 합성수지의치, 일반 합성수지의치의 순이였으며 금속상의 경우는 금속을 따라서 높은 등가 응력이 넓게 분산되었다.
4. 의치상 종류에 관계없이 동일 하중 조건하에선 점막에 나타나는 등가 응력의 크기및 분산양태는 유사하였다.
5. 하악골에서 등가 응력은 의치지지 부위에만 국한되지 않고 넓게 분산 되었으며 의치상 종류 및 하중 조건에 관계없이 치조제 후방 및 하악연의 후방 부위에 특히 높은 등가응력이 집중되었다.
6. 하악 중절치의 일점에 수직 하중을 가한 경우가 다른 하중 조건에 비하여 지지점과의 거리차이로 인하여 하악골에 가장 높은 등가 응력을 유발하였다.
7. 의치상 재료에 따른 하악 골에 발생되는 응력의 크기 및 분산에는 큰 차이가 없으나 금속상의 경우가 교합압을 분산하는데는 효과적이었다.