On functional strain in fixed mandibular reconstructions

II. An in vivo study

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Six linear strain gauges and one rosette strain gauge were used on one partially dentate subject to study various types of functional deformation in a six-unit conventionally designed fixed mandibular bridge and a five-unit cantilever fixed mandibular bridge. The results of this study show that the clinical straining pattern was complex and different from those recorded in laboratory model studies of the same case. It was therefore concluded that functional deformations of fixed dental appliances can be studied accurately only in clinical experiments. Fundamentally different straining patterns were observed between the conventionally designed bridge and the cantilever one. The clinical significance of these results are discussed in relation to prosthetic treatment with various types of fixed-bridge constructions. □ *Dental materials; fixed prosthetics; in vivo deformation*

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Laboratory studies of strain in fixed dental reconstructions under load have shown the appearance of complex surface straining patterns (1–4). The amount of strain in the various parts of these reconstructions has been found to vary not only with the loading and its way of application but also with the design and the type of bridge-supporting model system used (3).

In combined clinical and laboratory studies of strain in partial dentures, Glantz & Stafford (5) observed that in such reconstructions the surface straining pattern was also complex and that clinically relevant functional deformation patterns of partial dentures could not be determined from the results of laboratory experiments only. Similar results have been reported in studies of complete dentures (6).

Fixed dental appliances have better retention and clinical stability than removable dentures, and their functional deformation patterns may therefore perhaps be studied successfully under laboratory conditions.

To test whether functional deformation of fixed dental appliances may be tested relevantly under laboratory conditions, it was considered necessary to carry out an in vivo study of the functional deformation patterns of some fixed mandibular reconstructions previously studied in vitro.

Materials and methods

We have previously described in detail the test subject, the two types of bridge construction involved, and the experimental system used to record deformation in the bridge during loading (3).

In the clinical experiments the initial bridge construction tested was one including three veneer crown abutments on teeth 48, 44, and 43, with an intermediary bar between the crowns on 48 and 44. This bridge was tried in the mouth of the patient and found to fit well to the abutment teeth and to the distal prominence of tooth 42. When the intermaxillary contact relations were tested with a special wax, type Occlusal indicator

(Kerr, Romulus, Mich.), a premature contact was noted between the bar of the bridge and the distolingual cusp of tooth 16.

Before this contact was eliminated by grinding, however, the bridge was first retained to the abutment teeth with type Opotow temporary cement (Opotow, New York, N.Y.). The cement was mixed and handled in accordance with the manufacturer's instructions. After removal of the excess cement, the bridge was allowed to adapt to mouth conditions for another 10 min, during which the patient kept his teeth apart but his mouth closed while the signal conditioner and amplifier was balanced. Thereafter, during several strong bites by the test subject, the amplifier and the attached UV-oscillograph were calibrated to obtain maximum graphic excitation for the individual gauge signals. Finally, while the premature contact was still present, the test person carried out 10 2-sec maximum bites with 10-sec relaxation periods between each pair of bites.

The premature contact was then eliminated and, with an inverse waxing technique, found to have a maximum vertical dimension of about 0.4 mm. No additional occlusal interferences or disharmonies could be noticed after this correction.

The test subject was then allowed to rest for about 30 min. Another set of maximum bites was then completed while strain recordings were taken. During these recordings it was observed that gauge 4 was no longer giving signals. Gauge 4 was the only one placed on the occlusal surface of the bridge and therefore the only gauge exposed to direct load from opposing teeth. It is likely that during the initial 10 maximum bites the isolating silicone layer of the gauge was ruptured due to the direct loading, leading to saliva exposure and production of an electrical short circuit of this gauge.

After the end of this experiment the bridge was removed from the mouth and abutment crown 48 cut off under ample water cooling with a separation disc-type Dentig interproximal disc (R.H. Sittig Associates, Inc., USA). The rough surfaces were ground and polished, also under water cooling. Finally, the separated bridge components were tried and recemented, using the material previously described. After a 10-min adaptation period a new set of maximum bites and strain recordings was completed. Finally, strain recordings were taken while the test subject was performing 10 maximum bites with a wooden stick (diameter, 6 mm) in 4 different intermaxillary positions. The long axis of the stick was held approximately perpendicular to that of the experimental bridge. The tested positions were I) on the joint between abutment crown 44 and the bar; II) on the bar in a position approximately corresponding to the center of missing tooth 45 (3 mm from the distal surface of abutment 44); III) on the bar in a position approximately corresponding to the center of missing tooth 46 (10 mm from the distal surface of abutment 44); and IV) on the bar in a position approximately corresponding to the center of missing tooth 47 (20 mm from the distal surface of abutment tooth 44). The basic reason for using a wooden stick and not a bite gauge was that available bite gauges were too large and bulky to enable geometrically precise intermaxillary placements to be made, especially in the molar regions.

Results and discussion

The mean strain levels recorded by the individual gauges of the experimental bridge at maximum bites before and after the occlusal adjustment and after the removal of the distal abutment crown are given in Table 1. This table also gives the direction of the corresponding principal strains under the rosette gauge as calculated by the formular given by Glantz et al. (3).

Table 2 gives the corresponding strain levels and directions of principal strain during maximum bites on the wooden stick.

The results of Table 1 show that after occlusal adjustment a certain general decrease in strain could be noticed in the bridge. After the removal of the distal abutment crown, a major shift of the type of strain could be noticed. Thus, before removal of this crown all gauges were recording elongation in the bridge. After the removal, however, all gauges were recording

Table 1. Strain (true $\mu\varepsilon$) and direction of principal strain (degrees) in tested bridges at maximum bite ($n = 10$). Positive values denote elongation; negative values denote contraction

	Bridge with distal abutment tooth					
	Before occlusal adjustment		After occlusal adjustment		Bridge with distal cantilever bar	
Gauge no.	Mean	SD	Mean	SD	Mean	SD
1	371	90.4	258	37.9	−371	41.2
2	99	33.0	104	27.1	−160	14.2
3	366	39.4	278	25.6	−128	21.9
4	505	72.6	*		*	
5	462	52.1	284	49.1	−422	50.8
6	200	77.0	44	17.9	−121	16.0
7	145	47.2	104	34.2	−72	14.6
8	111	38.8	84	36.1	0	–
9	85	32.3	59	38.3	0	–
Direction of principal strain in relation to long axis of the bar	+68.0°		+63.8°		+2.0°	

* Gauge 4 failed during the running of the experiment.

Table 2. Strain (true $\mu\varepsilon$) and direction of principal strain (degrees) at maximum bites on a wooden stick placed in four different positions along a tested mandibular bridge ($n = 10$). Positive values denote elongation; negative values denote contraction

	Stick placed on soldering in regio 44/45		Stick placed on bar in regio 45		Stick placed on bar in regio 46		Stick placed on bar in regio 47	
Gauge no.*	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	80	26.7	−407	118.2	−780	39.1	−638	92.6
2	97	23.6	91	56.9	−149	29.9	−200	81.8
3	38	18.3	−367	52.2	−479	44.8	−311	38.6
5	−491	53.7	−728	66.7	−639	29.7	−390	85.1
6	70	22.5	226	60.9	−116	41.6	−220	95.8
7	57	16.2	194	53.7	115	44.6	−132	82.1
8	0	–	0	–	0	–	0	–
9	0	–	0	–	0	–	0	–
Direction of principal strain in relation to long axis of cantilever bar	33.5		69.8		80.3		85.8	

* Gauge 4 failed during the running of the experiment.

Table 3. Maximum and minimum stress and strain values (ε_{max}, ε_{min}, σ_{max}, and σ_{min}) and direction of principal strain (in relation to the long axis of the pontic bar) as recorded by a rosette strain gauge at maximum bites on a tested mandibular bridge before and after occlusal adjustment and before and after separation of distal abutment crown. Positive values denote elongation and tension, respectively, whereas negative values denote contraction and compression, respectively

	Principal strain (με)		Principal stress (N)		Direction of principal strain
	ε_{max}	ε_{min}	σ_{max}	σ_{min}	
A. Bridge with distal abutment crown before occlusal adjustment (centric occlusion)	425	41	423.8	173.6	68°
B. Bridge with distal abutment crown after occlusal adjustment (centric occlusion)	301	81	317.8	173.6	64°
C. Bridge after separation of distal abutment crown with distal cantilever bar (centric occlusion)	84	−372	−37.3	−333.5	2°
D. As under C but with stick placed on soldering in regio 44/45	67	39	97.1	77.5	34°
E. As under C but with stick placed on bar in regio 45	424	−700	185.4	−544.5	70°
F. As under C but with stick placed on bar in regio 46	181	809	−41.2	−363.0	80°
G. As under C but with stick placed on bar in regio 47	130	−544	−39.2	−290.4	86°

contraction instead. Furthermore, in the distal portion of the cantilever bar little or no strain at all was recorded.

The direction of the principal strain under the rosette gauge was virtually unaffected by the occlusal adjustment, but exhibited a marked shift of more than 60° upon removal of the distal crown (Table 3). The results given in Table 2 generally correspond with those given in Table 1. It is therefore clear that complex straining patterns appeared during the various types of loading on the cantilever bar. Such results can only be obtained from systems in which the teeth and/or their supporting tissues have a major mechanical influence. It is therefore likely that, at the loading of the cantilever bar, initial deformation took place in the highly elastic components of the supporting structures. The distance varied between these components and the point of load application, and, therefore, the geometry for load transfer must have varied between the four experimental situations.

Because the structures studied have a high degree of anatomical complexity, it is reasonable that no linear relationship could be found for the ratios between the recorded strain at maximum biting and the distance along the bar to the point of load application. A relative relationship was, however, observed indicating that relatively constant strain appeared in the supporting tissues somewhere in or in close proximity to the distal abutment tooth. Bearing in mind that mechanoreceptors have been reported to be present in these structures (7–9), it is likely that at certain strain levels receptors are activated, causing an inhibition of motor neuron impulses to the muscles responsible for the load application (10).

Several clinical conclusions can be drawn from this experiment. First, when cantilever pontics are incorporated in fixed dental appliances, the risk of technical failure is not particularly high in the actual cantilever parts of the construction but in those parts immediately proximal to the distal abutment crown. In particular, high strain levels were recorded mesial to this crown.

Second, when extensive fixed reconstructions are used in the treatment of persons with many missing teeth, the ongoing shift of the direction of principal strain at functional loading suggests that the distal abutment crown should be of the veneer type and have proximal walls as parallel as possible to minimize the risk of loss of retention.

Third, the risk of technical and biochemical complications should, at least in the waking state, decrease with decreasing bone support to the remaining teeth. In these cases the critical strain level for muscular deactivation should be reached more quickly owing to the decreased bone surface area. These conclusions are in accordance with clinical findings reported by Lindhe & Nyman (11) and Glantz & Nyman (10).

From the results of Tables 1 and 2 the principal maximum (ε_{max}) and minimum (ε_{min}) strains at the point of the bar directly beneath the center of the rosette gauge were calculated by means of the following formulae (12, 13):

$$\varepsilon_{max} = 1/2\,(e_2 + e_3) + 1/2\sqrt{2(e_3 - e_1)^2 + 2(e_1 - e_2)^2} \quad [1]$$

and

$$\varepsilon_{min} = 1/2\,(e_2 + e_3) - 1/2\sqrt{2(e_3 - e_1)^2 + 2(e_1 - e_2)^2} \quad [2]$$

where e_1, e_2, and e_3 are the strains registered by the different components of the rosette gauge.

The corresponsing principal maximum (σ_{max}) and minimum (σ_{min}) stresses were calculated by the following formulae (4):

$$\sigma_{max} = E\left[\frac{e_2 + e_3}{2\,(1 - \nu)} + \frac{1}{2(1 + \nu)}\sqrt{(e_2 - e_3)^2 + (2e_1 - e_2 - e_3)^2}\right] \quad [3]$$

and

$$\sigma_{min} = E\left[\frac{e_2 + e_3}{2\,(1 - \nu)} - \frac{1}{2(1 + \nu)}\sqrt{(e_2 - e_3)^2 + (2e_1 - e_2 - e_3)^2}\right], \quad [4]$$

where E is the modulus of elasticity of the used dental gold alloy (96,200 N/mm^2, according to the manufacturer), and ν is the Poisson ratio (0.33) (15, 16).

The calculated principal maximum stress and strain levels are given in Fig. 1. Generally speaking, as could be foreseen, the results given in Fig. 1 correspond with those obtained for the individual gauges and the components of the rosette gauge. A more complete picture of the deformation pattern in the bridge was, however, obtained with the analysis of the data given in Fig. 1. This figure shows that removal of the occlusal interference, although of considerable size, gave rise to only a slight decrease in the stress/strain profile of the bridge as given by the recorded ε_{max} and ε_{min} values and the ranges for stress and strain, respectively. In addition, the removal of the interference caused a small and fairly insignificant shift in the direction of the principal strain of the bridge underneath the rosette gauge. This is an observation that is in agreement with the clinical observation that even over long periods of time there seems to be no marked risk of mechanical failure in fixed bridges with occlusal interferences. Such interferences are more likely to cause the appearance of muscular or temporomandibular joint dysfunctions (17).

When the distal abutment crown was cut away, a complete change was, however, noticed in the deformation pattern of the bridge. At maximum bites, the stress underneath the rosette gauge shifted from tension to compression and the corresponding strain from elongation to mostly contraction. Furthermore, the direction of principal strain shifted by over 60°.

When the cantilever bridge was loaded at defined positions by biting on a wooden stick, it was evident that gross variations appeared in the recorded deformation pattern and strain values of the rosette gauge.

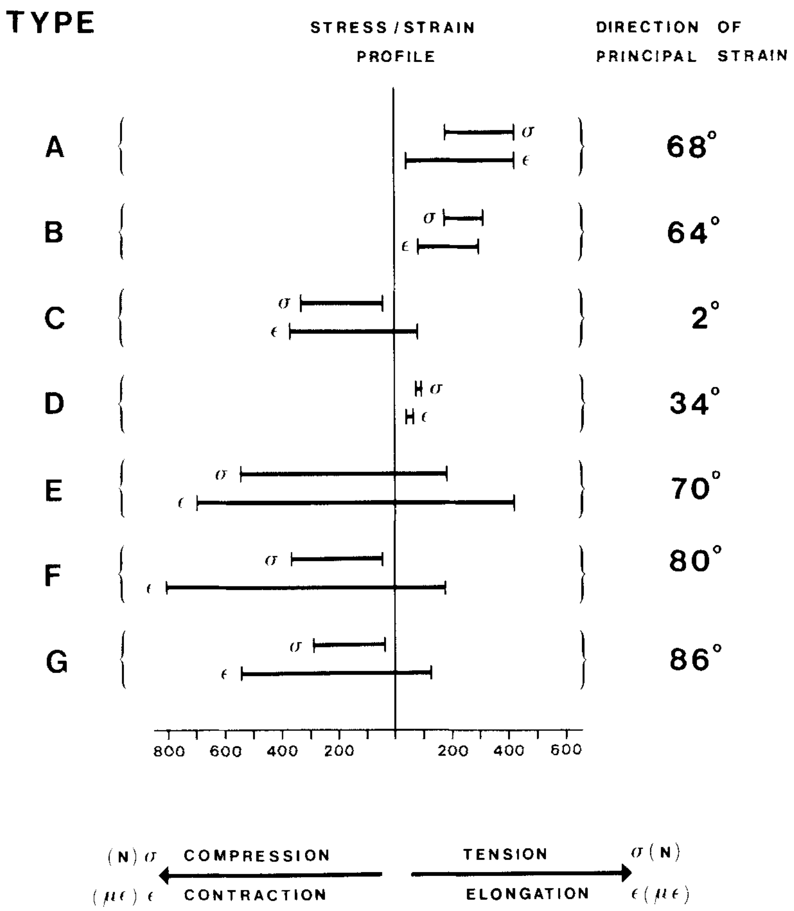

Fig. 1. Ranges of stress (σ) and strain (true με) and direction of principal strain (in relation to long axis of pontic bar) as recorded by a rosette strain gauge at maximum bites on a test mandibular bridge before and after occlusal adjustment and before and after separation of the distal abutment crown. Type A denotes a bridge with distal abutment crown before occlusal adjustment; Type B, a bridge with distal abutment crown after occlusal adjustment; and type C, a bridge after separation of distal abutment crown (with distal cantilvever bar). Types D, E, F, and G denote the same bridge situation as under C. In D, however, a stick was placed on the soldering in regio 44/45. In E this stick was placed on the bar in regio 45, in F on the bar in regio 46, and in G on the bar in regio 47.

Thus, when the point of loading was located between the crowns of 44 and 45, probably because a more or less axial loading situation was created in relation to abutment tooth 44, minor deformations were recorded in a direction of principal strain, varying by less than 35° from the direction of strain at maximum bites in intercuspal position.

As soon as the loading point was moved distally to regio 45, dramatic increases were, however, recorded both for stress and strain. At the same time the direction of principal strain shifted by about a further 35° and now came close to the directions recorded before removal of the distal abutment crown. In this cantilever situation a different and more alarming stress/strain profile was also created.

With the type of strain gauge technique used in this study only surface strain can be recorded. Other types of strain are certainly also present in dental appliances under load. Because metallic constructions with little or no inherent stress were studied and because failures due to overstrain originate at the surface, the technique used was, however, considered valid and useful.

When the results of the clinical recordings were compared with those obtained in laboratory experiments with various types of model system (3), no direct correlation was found. The observation that in vivo deformations in a fixed dental appliance cannot easily be even approximately simulated in anatomically precise models of various mechanical designs is in agreement with previous studies of both partial (5) and complete dentures (6). Obviously, therefore, in dental systems, including fixed dental appliances of certain dimensions, the initial deformations are to a major extent monitored by the mechanical properties of the biological components of these systems—that is, by the teeth, their periodontal membranes, and supporting osseous components. Even if, from a strictly theoretical point of view, it could be possible to create relevant mechanical models of masticatory systems and their incorporated prosthetic appliances, in combination with the well-known wide individual morphologic variability, the results of this study indicate that for practical purposes relevant information about the functional deformations in fixed dental appliances can be accurately obtained only from in vivo studies.

Owing to these highly individual morphological variations it is of course possible that the results obtained from in vivo studies of a person have little or no relevance in other cases than the one actually studied. Whether this is the case or whether general conclusions may be drawn from studies of typical cases, such as the ones used in this study, will be further investigated.

If some kind of preliminary studies with, for example, strain lacquer have to be performed to place strain gauges in as relevant locations and directions as possible, it will probably be at least as relevant to perform preliminary experiments on simple models as on models of more complex design.

In this study a temporary cement was used to retain the bridge, to make possible the necessary changes in the experimental bridge. The basic mechanical properties of temporary cements are inferior to those of permanent ones (14). Under the present experimental conditions, however, owing to the type and dimensions of the abutment crown preparations neither the stress on the cement films nor the times of load application were thought to have reached magnitudes high enough to influence significantly the recorded functional strain values (18). No clinically recordable signs or indications of crown displacements or loss of retention were thus observed during the running of the experiments.

When the results of this study are compared with studies of the loading generated at maximum bite, it is obvious that, even when the previously mentioned lack of correlation with the calibration situation is taken into consideration, the loading at maximum bites must have been of approximately the same magnitudes as those reported by Helkimo et al. (19)—that is, somewhere between 100 and 700 N.

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