On functional strain in fixed mandibular reconstructions

I. An in vitro study

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Six linear strain gauges and one rosette strain gauge were used on three different types of models prepared from one partially dentate subject, to study loading deformation in a six-unit fixed mandibular bridge. The bridge was mounted on each of the models on an adjustable articulator and loaded in a universal testing machine at loading levels ranging from 0 to 491 N. The results showed considerable differences between the three types of model, with regard to both the magnitude of the recorded strains for the individual gauges and the calculated direction of the principal strains under the rosette gauges. The findings indicate that the mechanical properties and the design of the supporting structures have a major influence on the functional deformation of fixed dental appliances. □ *Dental materials; fixed prosthetics; in vitro deformation*

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In designing fixed dental appliances a major objective is to obtain the rigidity necessary to distribute applied forces evenly over the supporting tissues.

To prevent failure occurring in a prosthetic reconstruction, it is mandatory to locate and define the dimensions and shape of each component of the reconstructions—that is, abutment teeth, luting cement, crowns, pontics, and soldered joints—in such a way that not even maximum stress levels will create an unfavorable strain in any portion of the reconstruction (1, 2). When there are few available abutment teeth or when these teeth are unfavorably distributed or make unfavorable intermaxillary contacts, it is more difficult to avoid permanent deformation or fractures in bridges during their long lifetime (3).

The forces generated during biting in dentate persons have been studied by Howell & Manly (4) and Helkimo et al. (5). These studies concluded that the maximum force on a single tooth varies between 383 and 880 N for molars and between 176 and 226 N for incisors.

The general location and types of stresses in some common dental bridge constructions have been discussed by Mahler & Terkla (6), Brumfield (7, 8), and Weinberg (9). In none of these reports, however, were any experimental studies presented.

In laboratory studies, Craig & Peyton (10, 11) and Tillitson et al. (12) have examined the strain in some bridge constructions, using strain lacquer and linear strain gauges. They all found complex distribution of surface strain for different loading conditions and bridge designs.

In clinical studies of the rigidity of mandibular partial dentures and maxillary complete dentures, Glantz & Stafford (13, 14) observed that in removable dentures strain is highly complex and that determination of the functional deformation pattern in such dentures can only be obtained in clinical experiments. Glantz & Stafford (13) also showed that with alteration in the design of

the frame of partial dentures, changes appeared both in the direction of the principal strain line and in the magnitude of the maximum strain at a particular point on the frame work.

Since fixed bridges have better retention and stability on underlying tissues than partial dentures it was considered worthwhile to perform a laboratory study on the deformation pattern of some common types of mandibular fixed bridge constructions.

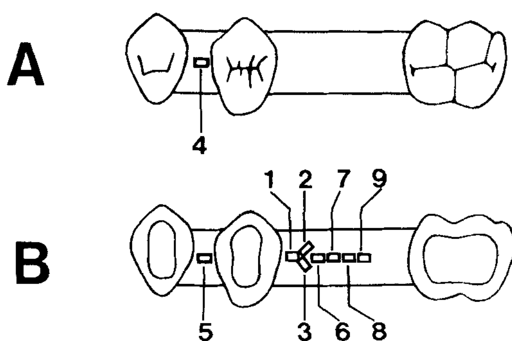

Fig. 1. General outline of the position of strain gauges (nos. 1–9) on a tested fixed mandibular bridge. 1A shows the occlusal and 1B the cervical surfaces of the bridge.

Materials and methods

One partially dentate male, 34 years of age, was used as the test subject. All his maxillary teeth were present, whereas in the mandible the remaining teeth were 48, 44, 43, 42, 41, 31, 32, 33, 34, 35, and 37. The subject considered himself to be in good general health and was found to be in good oral health at oral examination.

The subject was selected for restorative prosthetic treatment including a fixed bridge, for which veneer crown preparations were made on teeth 48, 44, and 43. On the buccal surfaces of preparations 44 and 43, additional dentin was removed to enable incorporation of facings in the crowns.

By means of individual impression trays and conventional impression techniques complete mandibular and maxillary impressions were taken in a silicone impression material, type President (Coltène A.G., Altstätten). Stone models were then made in Vel-Mix (Kerr Europe, Scafati). These models were mounted on an articulator type Dentatus ARL Special (Dentatus A.B., Stockholm), using standard clinical and laboratory procedures including the use of face bow registrations and retruded position indices.

On the mandibular model an experimental bridge construction was manufactured in a dental gold alloy type III (A-D C-guld, J. Sjöding & Co., Solna) by means of standard production procedures. The bridge consisted of veneer crowns on 48, 44, and 43 and a bar between 48 and 44. The bar was cast together with the crown on 48, whereas the crowns on 44 and 43 were cast in one piece. The bar was soldered to the crown on 44 with a solder for the temperature range 778–815°C (Ädelmetall A.B., Malmö). The bar had a total length of 24 mm, a width of 7 mm, and a height of 2 mm. The design of the experimental bridge is given in Fig. 1.

Nine strain gauges were attached to various parts of the bridge with an adhesive-type M-Bond 43-b Adhesive (Micro-Measurements, Romulus, Mich.). Gauges 1, 2, and 3 were the components of a rosette gauge, type WA-09-030-WR-120 (Micro-Measurements), whereas gauges 4 to 9 were linear gauges, type EA-09-031-MF-120 (Micro-Measurements). The resistance was 120.0 ± 0.5 Ω for all the gauges except nos. 4 and 5, which had a resistance of 120.0 ± 0.2 Ω. The gauge factor was 2.08 for the components of the rosette gauge, 2.135 for gauges 4 and 5, and 2.05 for gauges 6 to 9. To isolate the gauges for later use in the oral cavity, they were covered with a silicone material, type 314 ORTV (Dow Corning Co., Midland, Mich.). The position of the gauges are shown in Fig. 1.

The gauges were first connected with two wires to a coupling box, type DC-37S (McMurdo, Portsmouth), then with three shielded wires to a strain gauge conditioner and amplifier, type 2100 (Vishay Intertechnology Inc., Malvern, Penn.), and finally with a special cable to a UV-oscillograph, type SE 6150 Mk 2 (SE Labs, EMI Ltd., Feltham). To extend the balance of the

gauge signals, in the strain gauge conditioner and amplifier, resistor R7 with an original resistance of 70 kΩ was substituted for one having a resistance of 20 kΩ.

The articulator with its mounted models and bridge was positioned in a Type Alvetron universal testing machine (A.B. Lorentzen & Wettres Maskinaffär, Stockholm) in such a manner that compressive forces could be applied in the intercuspal position.

With a load increase of 196 N/min the models were loaded in compression for 150 sec—that is, to a maximum load of 490 N—while recordings were taken of the strain in the individual gauges.

All registrations were performed in a thermo-controlled environment (temperature, 21 ± 0.5°C), in which the articulator with its mounted models and the bridge had been stored for more than 24 h before each experiment.

After completion of these experiments, the mandibular model (I) was removed from the articulator and cut to separate the three abutment models from each other and from the rest of the model. Special Pin-dex holding pins (Whaledent Inc., New York, N.Y.) were then attached to the separated dies and retention rings for the pins secured in the model. A repeated set of experiments was carried out with this new model (II) in the universal testing machine.

Finally, the space between the dies and the model was filled with a silicone impression material, type President medium (Coltène A.G.), which was allowed to set for 30 min at a load of 245 N, and another set of experiments was performed on this final model (III).

Studies of some possible errors of the method

A. The temperature dependence of the gauges was provided individually by the manufacturer and given on the data sheets attached to the respective gauges. The information on these sheets showed that none of the gauges used had a difference of more than 20 $\mu\varepsilon$ between the gauge factors and apparent strains in the temperature range 20–37°C.

B. The time dependence of the gauges and the conditioning and recording systems were checked eight times, each time over a period of 60 min. No changes could be detected during these experiments.

Results and discussion

The results of the recorded strain in the gauges on the experimental bridge are given in Tables 1–3 and Figs. 2–4 for the three experimental situations applied. Tables 1–3 also give the directions of the principal strain lines under the rosette gauge, as compared with the long axis of the bar. The calculations of the direction of the principal strain were made according to the formula (13):

$$\mathrm{Tan}\, 2\theta = \frac{2e_1 - e_3 - e_2}{e_3 - e_2}, \qquad [1]$$

where θ denotes the angle between the direction of the principal strain line and that of the long axis of gauge 3, and e_1, e_2, and e_3 are the strains registered by the different gauge components. A positive angle denotes an angle counter-clockwise to the direction of gauge 3 and a negative one denotes a clockwise-directed angle. In this context it should be noted that the rosette gauge was mounted in such a manner as to give a 45° counter-clockwise angle between gauge 3 and the long axis of the bar of the bridge.

The principal maximum (ε_{max}) and minimum (ε_{min}) strains at the point of the bridge beneath the centre of the rosette gauge were calculated by the following formula (15, 16):

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

and

$$\varepsilon_{min} = \tfrac{1}{2}(e_3 + e_2) - \tfrac{1}{2}\sqrt{(e_3 - e_2)^2 - (2e_1 - e_3 - e_2)^2} \qquad [3]$$

When the results of Tables 1–3 and Figs. 2–4 were compared, considerable differences were noticed both between the recorded strains and the directions of the calculated principal strain lines for the dif-

Table 1. Strain (true $\mu\varepsilon$) and direction of principal strain in a fixed mandibular bridge at various levels of intercuspal loading (N) on a solid plaster model (n = 10) as recorded by nine strain gauges (G1–G9). (Positive strain values denote elongation and negative strain values denote contraction)

	Strain																		Directions of principal strain (under gauges 1, 2, and 3 in relation to the long axis of the bar)
	Gauge 1		Gauge 2		Gauge 3		Gauge 4		Gauge 5		Gauge 6		Gauge 7		Gauge 8		Gauge 9		
Load	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
49	62	0	17	6.3	33	0	−26	8.8	−41	6.6	49	0	32	0	30	0	38	0	83.9°
98	114	8.3	43	0	50	0	−26	8.8	−99	6.6	84	7.3	74	8.8	68	8.1	62	7.3	88.5°
147	165	10.7	64	7.7	74	9.3	−39	8.8	−129	6.6	129	0	106	8.8	95	8.1	84	7.3	88.5°
196	217	8.3	84	0	90	9.3	−48	0	−161	0	162	0	143	0	125	8.1	110	7.3	89.3°
245	262	8.3	101	6.3	114	7.6	−65	0	−194	6.6	194	0	165	8.8	148	0	136	8.9	88.2°
294	308	8.3	114	6.3	131	7.6	−68	7.2	−219	0	226	0	197	8.8	178	0	159	7.3	88.5°
343	346	10.7	129	6.3	151	0	−77	7.2	−243	7.8	258	0	223	0	199	8.1	175	7.3	88.5°
392	383	8.3	141	0	172	7.6	−74	8.7	−267	6.6	291	0	242	7.2	217	8.1	191	7.3	88.0°
441	428	8.3	152	6.3	191	9.3	−68	13.4	−290	6.6	320	7.3	271	0	237	0	210	0	87.8°
491	470	6.8	163	7.7	211	15.0	−60	13.4	−308	0	346	8.9	290	7.2	264	6.7	236	8.9	87.6°

Table 2. Strain (true $\mu\varepsilon$) and direction of principal strain in a fixed mandibular bridge at various levels of intercuspal loading (N) on a cut plaster model (n = 10) as recorded by nine strain gauges (G1–G9). (Positive strain values denote elongation and negative strain values denote contraction)

	Strain																		Directions of principal strain (under gauges 1, 2, and 3 in relation to the long axis of the bar)
	Gauge 1		Gauge 2		Gauge 3		Gauge 4		Gauge 5		Gauge 6		Gauge 7		Gauge 8		Gauge 9		
Load	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
49	208	10.3	51	10.5	96	8.4	73	10.6	−82	14.6	320	0	337	9.6	399	9.1	410	19.0	85.3°
98	353	8.0	84	9.6	158	40.2	107	21.3	−107	9.2	533	17.9	546	10.5	580	9.1	517	0	85.5°
147	484	9.6	130	7.4	211	4.8	65	21.3	−66	9.2	694	12.4	734	11.7	627	9.1	611	11.8	86.3°
196	550	10.6	154	9.6	213	68.7	22	21.3	−21	14.6	777	11.5	828	9.6	709	40.2	666	11.5	87.7°
245	604	9.6	172	7.4	235	79.1	17	9.6	−16	9.2	837	9.4	875	0	786	14.3	700	11.5	87.8°
294	640	0	194	8.0	257	83.8	17	9.6	−12	11.3	888	12.4	927	11.7	886	0	726	0	87.9°
343	670	10.8	203	7.3	263	87.2	13	11.8	−21	14.6	946	11.1	974	19.0	915	11.1	747	0	88.0°
392	696	7.4	212	6.8	265	87.2	22	21.3	−29	18.2	977	9.4	1008	17.9	947	0	773	11.5	88.3°
441	718	7.4	217	6.8	274	90.6	26	17.9	−25	22.6	999	17.7	1033	11.7	967	0	790	0	89.1°
491	730	11.0	225	5.5	274	93.9	30	32	−37	32.8	1021	11.5	1057	11.7	999	11.1	811	0	88.5°

Table 3. Strain (true $\mu\varepsilon$) and direction of principal strain in a fixed mandibular bridge at various levels of intercuspal loading (N) on a composite plaster and silicone model (n = 10) as recorded by nine strain gauges (G1–G9). (Positive strain values denote elongation, and negative strain values denote contraction)

	Strain																	Directions of principal strain (under gauges 1, 2, and 3 in relation to the long axis of the bar)
	Gauge 1		Gauge 2		Gauge 3		Gauge 4*	Gauge 5		Gauge 6		Gauge 7		Gauge 8		Gauge 9		
Load	Mean	SD	Mean	SD	Mean	SD		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
49	103	8.5	40	6.5	41	9.3		−108	6.3	165	7.3	258	13.3	240	8.0	236	8.9	89.8°
98	283	7.0	62	7.8	148	14.0		−210	6.3	499	21.0	576	7.2	521	8.0	486	0	83.2°
147	388	0	51	7.8	228	9.3		−299	7.6	734	24.6	905	20.7	804	10.4	723	8.9	80.2°
196	419	0	40	6.5	252	11.9		−267	6.3	763	21.0	1128	7.2	995	0	886	7.3	79.4°
245	441	8.5	23	7.8	295	9.3		−233	6.3	819	8.9	1191	7.2	1050	6.6	928	8.9	77.1°
294	457	13.8	0	0	329	9.3		−205	6.3	864	8.9	1252	8.8	1100	6.6	970	0	75.3°
343	469	7.0	−23	7.8	356	14.0		−177	6.3	899	8.9	1284	8.8	1132	8.0	1002	0	74.0°
392	475	8.5	−34	7.8	372	7.6		−164	6.3	919	7.3	1313	8.8	1161	8.0	1023	7.3	73.2°
441	482	0	−43	0	378	9.3		−138	0	938	11.5	1332	8.8	1173	6.6	1039	7.3	73.1°
491	482	0	−49	12.7	389	7.6		−117	7.6	945	8.9	1342	13.3	1197	6.6	1051	0	72.5°

* Gauge 4 failed during the course of the experiment.

ferent gauges and among the three experimental situations. Thus, it is obvious that on the cutting of the stone model (II), the deformation of the bridge shifted from a fairly uniform and simple pattern—shown, for example, by the almost 90° angle between the principal strain line and the long axis of the bridge, with approximately linear stress/strain relationships for all the gauges (Fig. 2)—to a complex strain pattern with non-linear stress/strain relationships, especially at lower stress levels (Fig. 3).

When an intermediate silicone layer was incorporated between the model components (III), an even more complex stress/strain relationship and straining pattern was observed (Fig. 4).

At increased stress levels fairly linear stress/strain relationships were achieved in model situations II and III. This indicated that in these experimental situations the composite models had shifted to mechanically less complex ones, probably through deformation in the models themselves.

The differences between the data of Fig. 2 and Figs. 3 and 4 indicate that, in the experimental situation used, the recorded strain was markedly influenced by the design and mechanical properties of the models.

Biological systems in which dental bridges are incorporated clinically are extremely complex from the mechanical point of view and of less inherent rigidity than stone models. The tissues supporting dental bridges are themselves both of a composite and anisotropic nature and often exhibit gross morphologic variations. Moreover, the direction of the functional load can never be fully standardized in a model situation.

Even though masticatory systems are known to be mechanically complex and model systems II and III were found to have complex stress/strain relationships, it has not been demonstrated that either or both of these two models were more relevant than model system I in comparison with the clinical situation.

In this study the strain gauges were positioned in areas of the bridge construction where clinical observation has shown that mechanical failures appear (17). Through explorative use of a strain lacquer it would

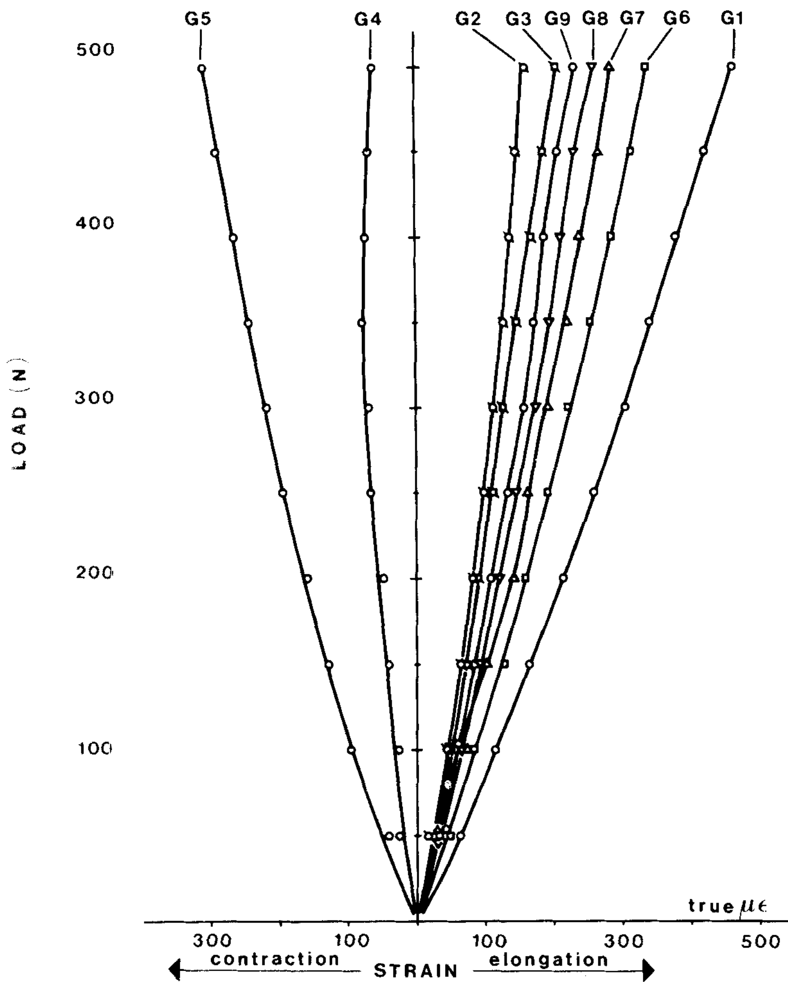

Fig. 2. Strain (true με) in a fixed mandibular bridge at various levels of intercuspal loading (N) on a solid plaster model as recorded by nine strain gauges (G1–G9).

have been possible to obtain information about the direction of the principal surface strain lines in the bridge before the application of the gauges. Because such a procedure could only have had relevance for the first (I) of the three experimental situations used and because this study was fundamentally of a comparative and not of an absolute nature it was, however, considered adequate to incorporate a rosette strain gauge for determination of the direction of the principal strain in an area known to be a comparatively frequent location of mechanical failures in dental bridge constructions (1).

A slight modification was made of the strain gauge conditioner and amplifier used in this study, to ensure that the clinical strain measurements were performed in a manner that did not interfere with muscular activity. For this reason and also because of the small size of the gauges only two wires per gauge were used to connect the gauges to the coupling box. Ideally, three wires are used per gauge to reduce as much as possible the negative effects on the gauge signals from connecting wires. When only two gauge wires were used, with the original design of the amplifier, problems were also encountered when attempting to balance the bridge signals before the beginning of each set of loadings. When an original resistor was substituted for one having a lower resistance,

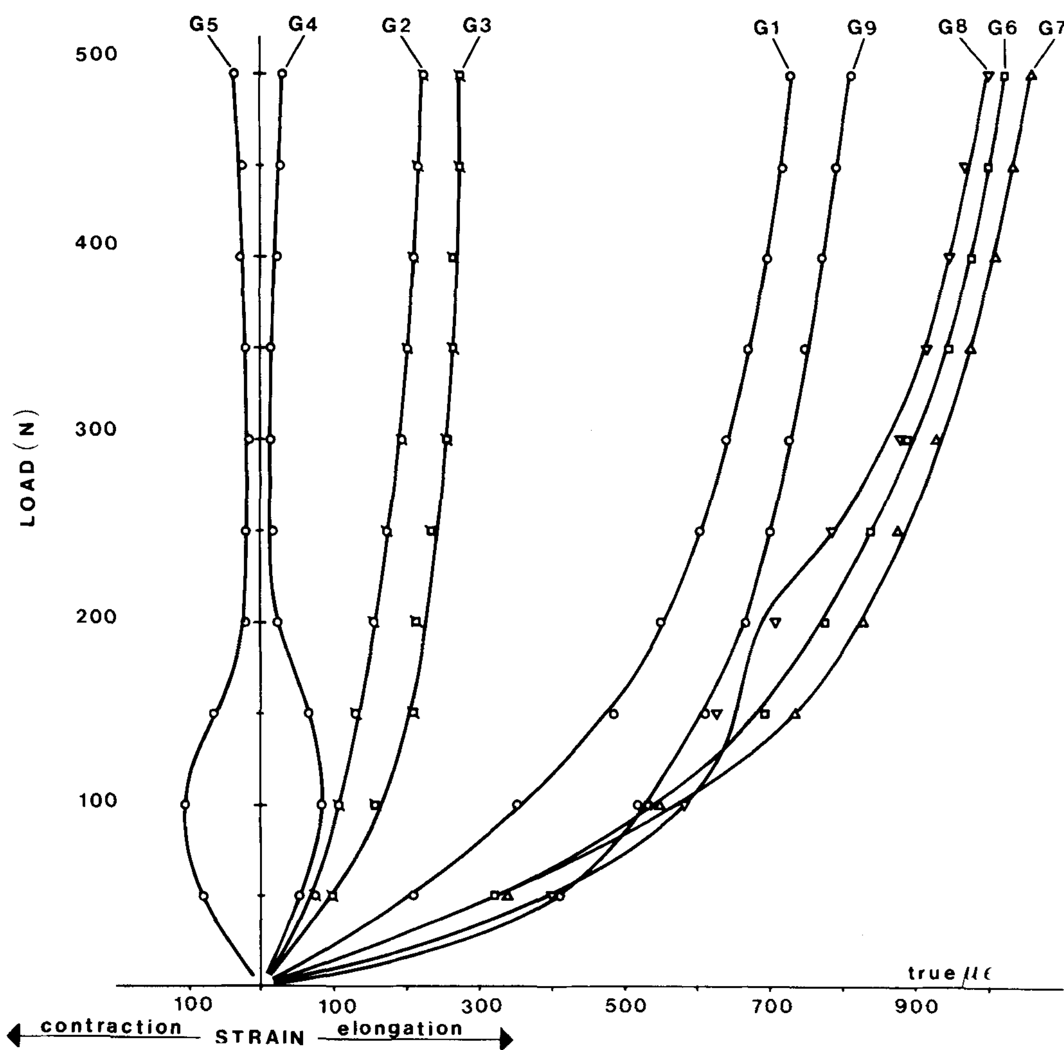

Fig. 3. Strain (true $\mu\varepsilon$) in a fixed mandibular bridge at various levels of intercuspal loading (N) on a cut plaster model as recorded by nine strain gauges (G1–G9).

these problems were, however, resolved. A slight drift of the base lines of gauge signals could then occasionally be noticed. If strain gauge signals are to be more or less continuously recorded at constant or varying stress levels over long periods of time (weeks to years), such a drift may cause serious problems in analyzing the records. Prolonged strain gauge studies are common in most fields of technology. Under the experimental conditions of this study, however, in which loads were applied for only short periods of time, signal drifting did not cause any problems.

It is concluded that it cannot be proved whether in vitro determinations of the deformations of fixed prosthetic appliances have clinical relevance. To make such a conclusion possible and compare the three laboratory models with the true clinical situation, it was decided to extend this study into an in vivo one.

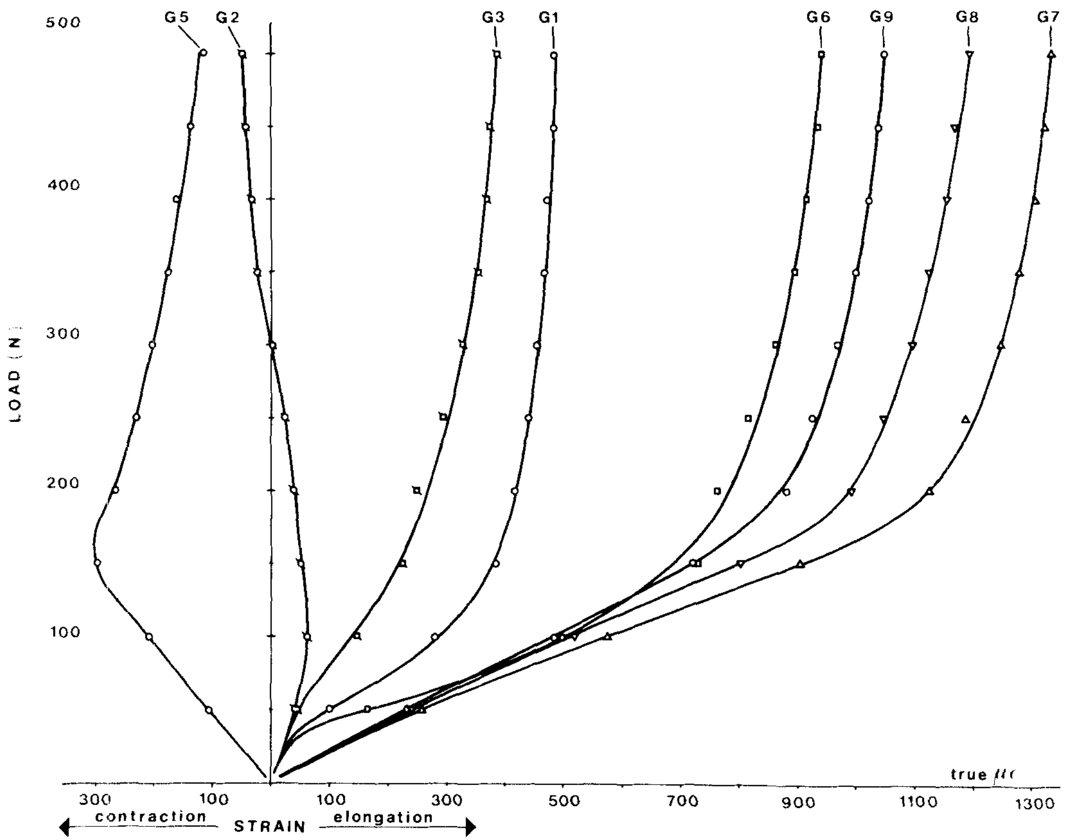

Fig. 4. Strain (true με) in a fixed mandibular bridge at various levels of intercuspal loading (N) on a composite plaster and silicone model as recorded by eight strain gauges (G1–G3 and G5–G9).

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