THE DIRECTION OF TOOTH MOVEMENT WITHIN THE PERIODONTAL SPACE. THE OMNIDIRECTIONAL TRANSDUCER

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THE directional aspects of tooth displacement within the periodontal space in response to applied forces are clinically important. During orthodontic treatment forces are applied to the teeth with the intention of repositioning them to more favourable locations, and in restorative dentistry the coronal morphology may be altered so that the forces originating from the lips, cheeks and tongue, and the muscles of mastication may give rise to tooth displacements with different directions from those which existed prior to treatment (Weinstein 1963). In both instances changes occur in the periodontium which result in the tooth taking up a new position in the dental arch. These changes are related in part to the direction of tooth displacement because, among the many histological changes which can be demonstrated, bone resorption occurs in that part of the alveolus towards which a tooth is being repositioned. The direction of tooth displacement in response to applied forces is governed by factors such as the shape and length of the root, the characteristics of the fluid content of the periodontal space, the periodontal fibre volume, concentration, composition and orientation, and the surrounding alveolar bone (Lewin 1970). These factors, which have been analysed by Dreyer (1967), can be thought of collectively as restraining influences which tend to oppose tooth displacement. Because of the diversity of these restraining influences, the tooth may not be displaced in the direction of an applied force.

A review of the available literature reveals that there is a variation in the pattern of displacement of a tooth in response to forces of different magnitude and duration. Mühlemann (1967), in an extensive review of this subject matter, refers to horizontal and axial tooth movements and the influence of rotatory forces.

In the main, the direction of root displacement is inferred from the displacement of the crown, or the direction of the applied force. Thus, for a given force applied to the labial aspect of an upper incisor there may be a palatal displacement of the cervical, and a labial displacement of the apical part of the root, or the whole root may be displaced palatally. To overcome some of the disadvantages of unknown root displacement in response to applied forces, Picton (1962) controlled the mesial and distal displacements of the crown of a test tooth while applying forces which tended to intrude the tooth; and Parfitt (1967) limited the labio-palatal displacements of the crown of a test tooth while applying forces which were intended to produce axial displacements of the root. In each of these experimental models only two of the directional variables were controlled. The aforegoing discussion renders it clear that the direction of root displacement in response to applied forces requires further investigation.

A tooth can be displaced in one or in a combination of two or more of six basic motions. The translational and rotational components expressed in dental terminology are:

1) Apical and occlusal displacement.	TRANSLATION
2) Mesial and distal bodily displacement.	
3) Buccal and lingual bodily displacement.	
4) Rotation about a 'long axis' or apico-occlusal axis.	ROTATION
5) Rotation about a mesio-distal axis.	
6) Rotation about a bucco-lingual axis.	

The relevant literature was searched for a *method* which could be applied to the measuring of the six basic motions of tooth displacement. It revealed that Lebow, as quoted by Perry (1962), designed and developed a subsonic wind tunnel balance which can measure the six basic motions of an aerofoil in a wind tunnel. The principle of the wind tunnel balance is based on the separation of force and moment with resistance strain gauges which detect or transduce mechanical deformations such as compressive, tensile and shearing strains. Essentially, the gauges are attached to a geometric configuration of beams which, when stressed, cause resistance changes in the gauges. These changes are measured by electronic equipment.

Lewin (1969) compared the directions of tooth displacement to the displacements of an aerofoil in a wind tunnel. The comparison is summarised in Table 1.

TABLE 1

Aeronautical Term	*Dental Term*
1) Lift	Apical or occlusal bodily displacement
2) Drag	Mesial or distal bodily displacement
3) Yaw	Buccal or lingual bodily displacement
4) Pitching Moment	Rotation about a bucco-lingual axis
5) Rolling Moment	Rotation about a mesio-distal axis
6) Yawing Moment	Rotation about an apico-occlusal axis

He suggested that Lebow's principles could be adapted to the design of an omnidirectional transducer which could be used to determine the direction of tooth displacement in response to applied forces.

THE DESIGN OF AN OMNIDIRECTIONAL TRANSDUCER

a) *The Resistance Strain Gauge as a Transducer.*

In 1856 William Thomson (Lord Kelvin) reported that the electrical resistance of some wires varied when they were subjected to tension. In 1938 Simmons of the California Institute of Technology and Ruge of the Massachusetts Institute of Technology developed a technique for bonding wire to a surface to be tested for strain. These investigations led to the development of the sophisticated bonded foil gauges in use today.

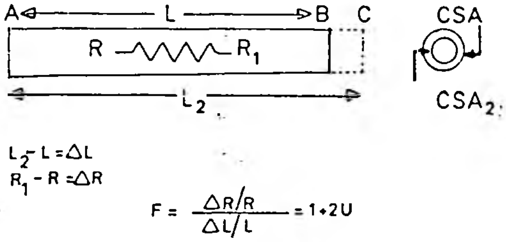


FIG. 1. Change in length and change in cross section as a function of change in resistance.

Fig. 1 is a diagramatic representation of the changes that occur in a length of wire subjected to tension. As the length (L) of the wire, AB, is tensioned to a new length, AC, that is, L_2, its resistance, R, changes fractionally so that it has a new resistance, R_1. The resistance change in the wire is therefore related to the strains in the stressed wire:

$$R_1 - R = dR = f((L_2 - L) = dL)$$

which is expressed in terms of a gauge factor, F, as:

$$F = \frac{dR/R}{dL/L} \text{ where}$$

dR = change in resistance.
R = initial resistance.
dL = change in longitudinal dimension.
L = initial longitudinal resistance.
F = gauge factor.

The gauge factor may also be expressed in terms of Poisson's ratio, defined as the ratio of the transverse contraction per unit dimension of a bar of uniform cross-section to its elongation per unit length when subjected to tensile stress:

$$\frac{CSA_2 - CSA = d\ CSA}{dL} = u$$

$$F = 1 + 2u$$

(Perry 1962)

Compression of the wire causes opposite dimensional changes to tension; the changes in resistance are also opposite.

Various elements and alloys are used in the production of resistance strain gauges, Ni, Cr, Mn, Cu, Fe, C, Pt, being the commonest. Each element has its own gauge factor; for example carbon has a gauge factor of +20 (approximately). Some material with the best overall characteristics of temperature stability, resistance, and stress equivalent can be achieved by alloying. Thus Constantan gauges, an alloy of Ni and Cu, were chosen for the omnidirectional transducer. They are 0.6 mm in length, have a gauge factor of 2.13, a temperature coefficient of resistance of 12×10^{-6} °C, (ohms/ohm/°C × 10^{-6}), are temperature-compensated from 10-120°C, and have a resistance of 120 ohms. When stressed the resistance of the strain gauge changes by very small amounts. For example, a 120 ohm gauge with a gauge factor of 2.0 which has been cemented to a piece of steel may change by only .008 ohms when the steel is subjected to a stress of 1000psi. Conventional ohmmeters are not sensitive enough to measure these small changes in resistance.

b) *The Wheatstone Bridge.*

This is an electrical circuit which can detect small changes in resistance, capacitance and inductance. Fig. 2 is a schematic diagram of a Wheatstone bridge.

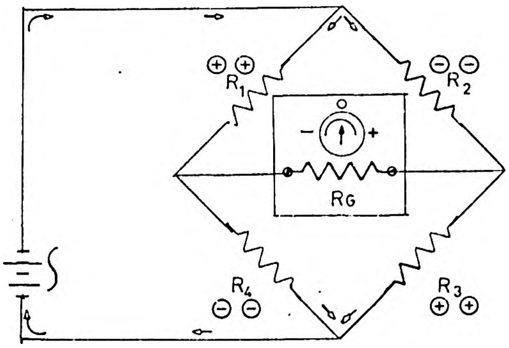


FIG. 2. The Wheatstone Bridge. The (+) and (—) signs indicate change in resistance.

If the resistance, R_1, is unknown and the resistances, R_2 and R_3 are the ratio legs, and R_4 is a resistance of known value, then if no current flows through the galvanometer resistance, R_g,

$$\frac{R_1}{R_4} = \frac{R_2}{R_3}$$

and

$$R_1 = \frac{R_2}{R_3} \times R_4$$

Under these conditions the bridge is said to be balanced. If the value of one of the resistances varies the bridge becomes unbalanced and current will flow through the galvanometer resistance, R_g. From Ohms Law this current is dependant on R and the voltage of the power supply. The current indicated by the galvanometer is therefore not a precisely linear function of the strain gauge resistance change in any leg of the bridge. However, this non-linearity is negligibly small for strains of several thousand micro-inches/inch (Perry 1962) and can be further decreased by dynamic regulation of the power supply voltage and current, and careful attention to the output impedance matching circuits. Although direct current can be used to power the bridge circuits used for detecting varying (dynamic) strains encountered in the measurement of tooth displacement (Lewin 1970), audio frequencies offer the possibility for pure dynamic strain measurement (Perry, 1962). When audio frequencies (carrier) are passed through the Wheatstone bridge they are modulated by any change in the resistance strain gauges in any leg of the bridge. If the carrier is then subtractively added to the modulated carrier as occurs in the demodulation stage of the associated electronic equipment, only the effects of the resistance changes in the strain gauges will pass on to the indicators.

In the direct current bridge the polarity of the voltages on either side of the galvanometer dictates the direction of the current flow. In the audio frequency bridge (AC) the galvanometer gives an indication of a proportional voltage difference. To keep track of the sign of the strain affecting the bridge a phase sensitive demodulator is necessary.

The current handling capability of a small strain gauge is limited. The output of the Wheatstone bridge circuit therefore requires amplification; this is relatively simple while the signal is in the audio range prior to demodulation. However, after demodulation differential amplifiers are required to amplify both the negative and positive phases of the output voltages. Both methods are employed with the omnidirectional transducer.

From the foregoing it can be seen that

a previously balanced Wheatstone bridge can be used to indicate dynamic strains. The outputs of the amplifiers are used to drive oscilloscopic, pen, and ultraviolet oscillographic recorders.

There is an initial imbalance in the whole system as a result of varying lead lengths, the strains developed during the cementation of the gauges, and the effects of stray inductance and capacitance. The latter reactances can be cancelled out by the addition or subtraction of suitable values of inductance or capacitance, while resistance imbalance can be controlled with suitable resistors.

c) *The Strain Gauge as a Directional Transducer.*

Referring to Fig. 3, resistance gauges R_1, R_2, R_3 and R_4 are cemented to a cantilever beam ABCD at its root. They are connected as shown in the circuit diagram in Fig. 2. When the beam is depressed in the direction MN, tensile strains are created at the root of the cantilever beam and the gauges R_1 and R_3 are tensioned. Their resistance increases. Because of their position in the Wheatstone bridge the change in resistance is additive. If the bridge was previously balanced it will now be unbalanced and this additive imbalance will be registered by the galvanometer. For example, if the galvanometer has a zero center setting, it may deflect towards the positive sign. At the same time the gauges R_2 and R_4 go into compression. The decrease in resistance is additive and because of their position in the bridge circuit they add to its imbalance. The galvanometer thus deflects further towards the positive sign. If the cantilever is now elevated in the direction NM, an opposite deflection of the galvanometer will occur. It is clear that strain gauges can be used as directional transducers. The magnitude of the directional change is subject to the factors governing the linearity of the system discussed above.

Although the greatest imbalance will occur if all the gauges in the bridge circuit are attached to the cantilever beam, it is possible to use only one or two to detect changes in strain. For instance gauges R_2 and R_4, (Fig. 3) or gauges R_1 and R_4 can be positioned at locations which are not associated with the strain as long as their positions in the bridge circuit is not altered. The remote resistance strain gauges can also be replaced by resistors of the same ohmic value as the gauges. When only two legs of the bridge are used for the detection of strain, the system is referred to as a half-bridge; and one which responds to opposite resistance changes when strained in a given direction is used in the omnidirectional transducer. In Fig. 3 these gauges are R_1 and R_2. Resistors replace R_3 and R_4 in the bridge circuitry.

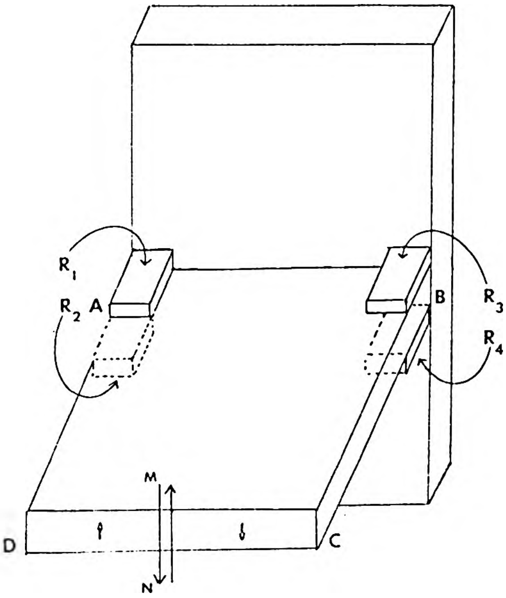
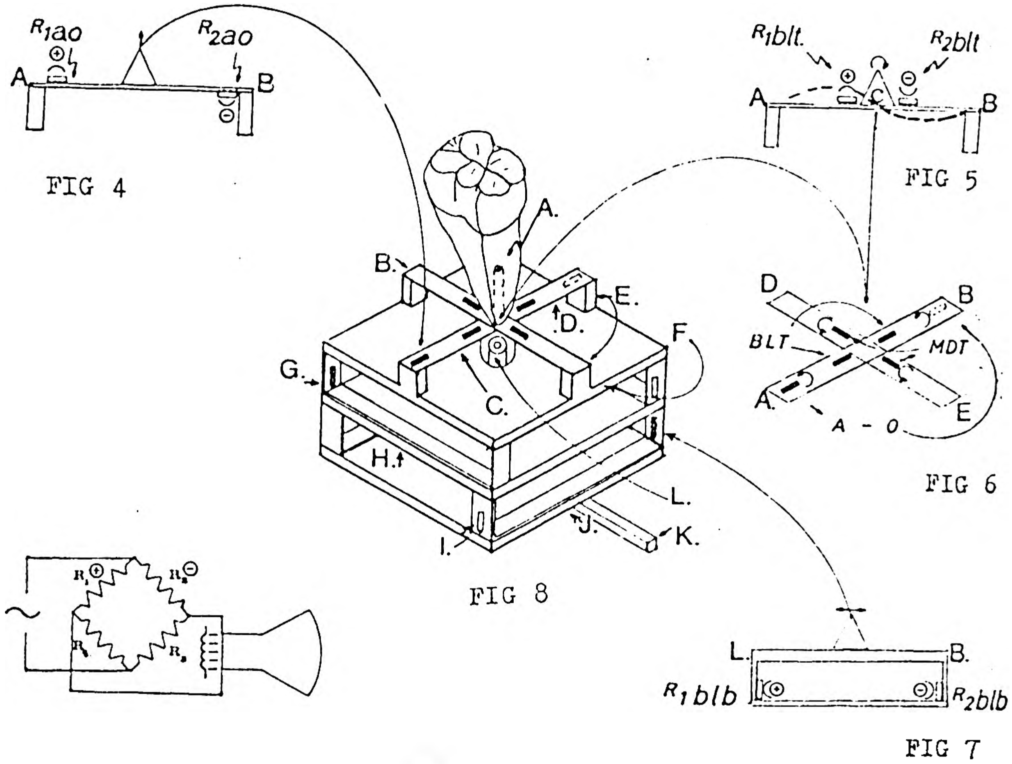


FIG. 3. The resistance strain gauge as a directional transducer.

d) *The Geometric Design of an Omnidirectional Transducer.*

This is illustrated in Fig. 8. It consists of 10 direction sensing beams, and the strains set up in each one alter the resistance in the strain gauges cemented to it when the tooth is moved. The changes which occur on the individual beams are tensional and compressional, and additive in each of five independent bridge circuits. In addition to the direction sensing beams there is a cylindrical rod centred on the beams which detects shearing strains when subjected to torque. It has its own bridge circuitry. To illustrate



FIGS. 4, 5, 6, 7, 8. Design of an omnidirectional transducer.

the principles of the individual direction sensing elements of the omnidirectional transducer, the design is segmented into Figs. 4, 5, 6, 7, 8.

Fig. 4 illustrates the method employed for measuring apical and occlusal translational displacement. Two active gauges are used in a half-bridge circuit. The beam AB is fixed at A and B. Raising the tooth causes the beam to bend so that compression strains are set up in gauge $R_{1\ (a\text{-}o)}$ which is located on top of the beam, and tension strains in gauge $R_{2\ (a\text{-}o)}$ which is located on its underside. Depressing the tooth causes opposite changes in the gauges. Raising or depressing the tooth causes elongation in both gauges and these effects, being of the same sign, cancel out. The respective imbalances are detected in a bridge circuit and displayed on an oscillographic recorder as apical or occlusal translational displacement.

Fig. 5 depicts the method for measuring buccal and lingual rotational displacements (tipping). As the tooth is tipped in the direction of the arrow, the beam AB bends about C in an S-shaped manner (dotted line). This bending causes tensile strains in the gauge $R_{1(blt)}$, and compression strains in gauge $R_{2\ (blt)}$, both of which are located on the top of the beam and close to its midpoint. Tipping in either direction is detected and correctly displayed on the recording equipment. As shown in Fig. 6, the buccal and lingual tipping gauges are located on the same beam as the apical and occlusal sensing gauges. Because of the symmetrical distortion, the latter are similarly strained when the beam, AB, is bent for buccal or lingual tipping; thus no significant output occurs or is measured by the bridge circuit recording apical and occlusal displacement.

Fig. 6 also shows the addition of a beam DE with two gauges positioned on the top side and located close to the centre. It has the same dimensions as the beam AB and forms a cross with it. The gauges on DE detect mesial and distal rotations (tipping) by the same principle as described for buccal and lingual rotations. However, shearing strains occur in gauges $R_{1\&2(a\text{-}o)}$, and $R_{1\&2(blt)}$ when the beam DE is bent during mesial and distal tipping. Since they are the same type of strain, there is negligible output from the bridges registering apical and occlusal, and buccal and lingual translation and rotation respectively. Similarly, shear strains occur in the beam DE when AB is bent and these likewise cancel out. There are no other gauges on the beam DE.

Fig. 7 outlines the method for detecting buccal and lingual translations (bodily displacements). As the tooth moves bodily from L to B gauge $R_{1(blb)}$ which is situated at the base of the vertical beam on its inner surface goes into compression; and gauge $R_{2(b'b)}$ which is located at the base on the inner surface of the other vertical beam is tensioned. The additive imbalance so created in a previously balanced bridge circuit is appropriately registered. Apical and occlusal translations will put either compressional or tensional strains on these gauges with negligible effect on the associated circuitry.

The principles employed for the detection of mesial and distal translations (bodily displacements) are the same as those used for buccal and lingual translations. Fig. 8 shows one of the gauges of the mesial and distal translational circuitry at G. Rotational displacements about the apico-occlusal axis are measured by gauges attached to the tooth support strut A (Fig. 8). Fig. 9 shows the tooth support strut to be a cylindrical rod XY; as it shears on itself at T, $R_{1(rot)}$ goes into compression and $R_{2(rot)}$ is tensioned. Additive imbalance occurs in the associated bridge circuitry which is registered as a positive or negative rotation about an apico-occlusal axis. Because the cylindrical rod is fixed to the centre of beams AB and DE (Figs. 6 and 8), the greatest bending during mesial and distal, and buccal and lingual rotation occurs at its point of fixation; this is in common with any cantilever. These rotations have no effect on the gauges on the cylindrical rod.

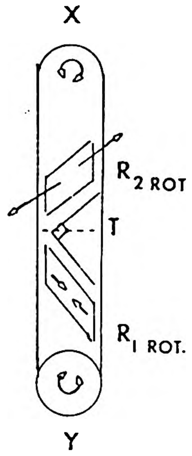


FIG. 9. Rotation about an apico-occlusal axis.

During apical and occlusal translation the gauges on the rod are affected in the same manner so that there is negligible registration in the circuitry associated with apico-occlusal rotation.

If the omnidirectional transducer is attached to a tooth the composite arrangement of beams, cylindrical rod, strain gauges and electronic equipment makes it possible to differentiate a displacement of the tooth into three translations and three rotations; these completely describe the displacement of a tooth in response to an applied force.

The information derived from the omnidirectional transducer can be used to specify the displacement of the whole tooth or any point in or on the tooth (Lewin and Dreyer, 1970).

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