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Assessment of the interfacial rigidity of bone implants from vibrational signals

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The applicability of an acoustoelectric technique to the *in vivo* assessment of the interfacial mechanical states for various bone implants has been shown by using *ex vivo* models. It has been found that the signal taken from an implant depends on the surrounding bone and the implant material to some extent as well as on the interfacial state.

1. Introduction

There are various materials which show excellent biocompatibility with bone; for example, (i) bioactive glass and glass ceramics, (ii) alumina, (iii) apatite, (iv) titanium and (v) carbon. Clinical and experimental studies show the possibilities of these materials for dental, orthopaedic and otological applications ((i) [1–6], (ii) [7–9], (iii) [9–11], (iv) [12, 13], (v) [14]). It is of importance to see when and how firmly they are united or closely in contact with bone after implantation. X-ray photography and finger-contact diagnosis, which were the only methods available in clinical use until quite recently, do not provide sufficient information. In a previous paper a simple acoustoelectric technique was described for assessing *in vivo* the interfacial rigidity between a dental root implant and the bone surrounding it [15]. A distinct signal difference was observed in animal tests of a bioactive implant and a non-bioactive one; the former and the latter were made of conical shell-like metal with coated bioactive glass (BG) and bioincompatible glass, respectively. It was shown to agree well with that obtained from corresponding *ex vivo* models.

The above technique has now been applied to clinical tests of BG-coated metal root implants at Iwate Medical University and Kagoshima University, Japan. Figs 1a to c are examples of vibrational signals taken from implants of about 10 mm length which were embedded under the protection of mucous membrane for over three months*. The signals show that the interfaces are rigid (Fig. 1a), slightly rigid (Fig. 1b) and non-rigid (Fig. 1c). After the mucous membrane was taken off, crowns were set on the implants of Figs 1a and b. The former implant functions well up to the present over two years after, while the latter was naturally extracted out within a half year; part of the periphery of this implant was found to have been united with bone. For the implant of Fig. 1c it was judged that the interface could not be expected to become rigid later. The implant was extracted out with only a small force. The whole periphery of it was confirmed to be covered with thin soft tissue.

On the basis of a large number of clinical data on BG-coated metal root implants, Miyasawa and his colleagues at Iwate Medical University and the author have found the following [16]. For long-term stability of a dental implant it is important to embed its root implant so that it is well fitted with the surrounding bone; however, an initial fit that produces very high interfacial rigidity is unnecessary. In general, a root implant is successfully united with bone in the case where the maximum amplitude of the vibrational signal taken a few months after implantation is very small; otherwise, it is naturally extracted out before or within a half year after a crown is set on it.

The above studies [15, 16] show that the acoustoelectric technique is useful for estimating different interfacial states of BG-coated metal root implants. It can possibly be applied to other implants as well. Fundamental experiments for such an application have been done by using various models of implant, bone and interface. The minimal detectable amount of non-rigidity of the interface has also been examined by using BG-coated metal root implants. In this paper the results are presented.

2. Measuring system

The measuring system used is the same as described elsewhere [15] (Fig. 2). It consists of a pulser–receiver, an oscilloscope and a pair of an acoustoelectric driver (AED) and an acoustoelectric receiver (AER). The pulser–receiver consists of a pulse generator, a signal amplifier and a contact tester; the last component is used only when an implant is invisible and made of metal. The AED and AER have simple structures as depicted in Fig. 3; in some cases, the needles shown are unnecessary.

The measuring principle is simple, as follows. The pulsed force, which is applied to an implant by lightly contacting the AED with it, induces a vibration characteristic of the interfacial rigidity between implant and bone. The vibrational signal is picked up by lightly contacting the AER with the implant. The needles of the AED and AER are usually contacted with an implant in the way shown in Fig. 4a; the signals of Fig. 1 were obtained in this way.

*Part of these data were presented by T. Kaneko and M. Ogino at the 1985 Biocompatibility and Biomaterials Gordon Research Conference which was held at Plymouth, New Hampshire.

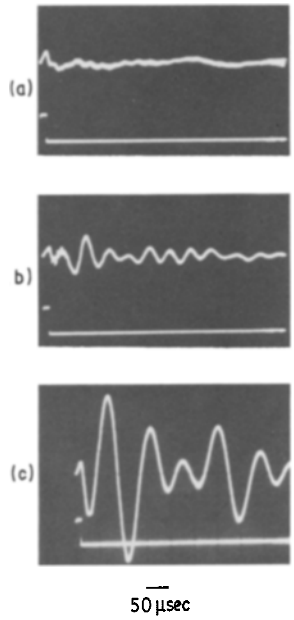

Figure 1 Vibrational signals taken from bioactive dental root implants in clinical use. Upper signals: output, lower signals: reference pulse. (a) Successful implantation, (b, c) unsuccessful implantation.

3. Experimental results

Implants and implant models used were

(i) BG-coated metal root implants;
(ii) rods of glass, plastic and metal;
(iii) tubes of metal;
(iv) plates of glass, ceramic, metal and plastic.

Dried jawbones of cattle, a plastic tube, a glass block, etc. were used in place of living bone.

Different mechanical states of the implant–bone interface were classified as follows:

(a) rigid (bone formation at the interface): signal of small amplitude and high frequency;
(b) slightly rigid: signal of medium amplitude and medium frequency or high and low frequencies;
(c) non-rigid (soft tissue formation at the interface): signal of large amplitude and low frequency.

Ex vivo models corresponding to the above interfacial states were as follows: implants or implant models were

(a1) wholly fixed with cyanoacrylate adhesive (CAd) or epoxy adhesive (EAd) to,
(a2) wholly fixed with a very thin layer of soft silicone adhesive (SAd) or liquid (Liq) to,
(b1) partly fixed with CAd or EAd to,
(b2) partly fixed with a very thin layer of SAd or Liq to,
(b3) wholly fixed with a thin layer of SAd or Liq to,
(b4) brought into close contact with,
(b5) mechanically fixed to (tight),
(c1) fixed with a thick layer of SAd or something like to,
(c2) mechanically fixed to (loose)

the models of living bone.

The scales of time, output voltage and input voltage in the vibrational signals shown below, including Fig. 1, are respectively 50 μsec, 0.1 V and 5 V per division, unless otherwise specified.

3.1. Femur model of rabbit

Animal femur is often used for experimental studies of bone implants. Fig. 5 shows a femur model of rabbit, which is made of a plastic tube of 36 mm length, 8 mm inner diameter and 10 mm outer diameter. Glass rods of 10.5 mm length and 2.5 mm diameter were put in the holes drilled through the tube and were bonded to it by using EAd and SAd. Figs 5a and b are the signals obtained from the top surface of each rod. We can see a clear difference between them. In Fig. 5a the interface is classified as slightly rigid, mainly because the greater part of the rod is not in contact with the tube. Fig. 5c is a signal from the plastic tube itself. The signal amplitude is fairly large.

3.2. BG-coated metal root implants in cattle bone

Figs 6a to c show the signals of three implants of the same size embedded in cattle bone, the thickness of which is about 10 mm; it is much thicker than the

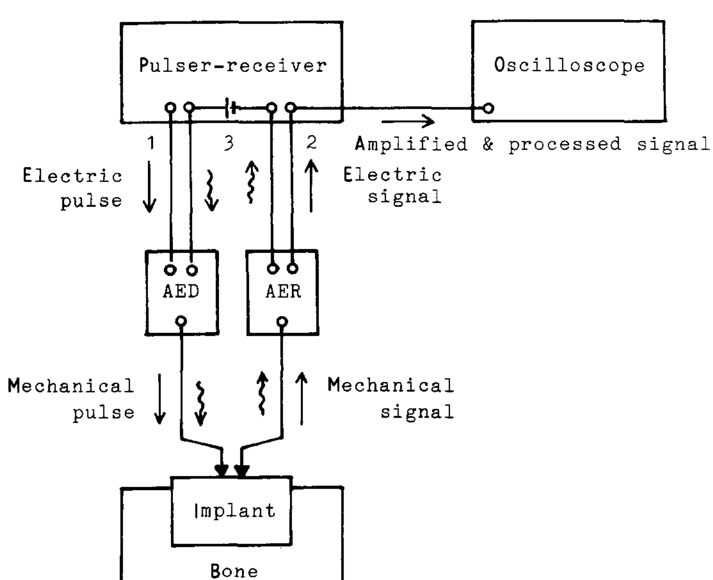

Figure 2 Experimental arrangement: (1) Pulse generator, (2) signal amplifier (60 dB, 20 kHz bandwidth), (3) contact tester, (AED) acoustoelectric driver, (AER) acoustoelectric receiver.

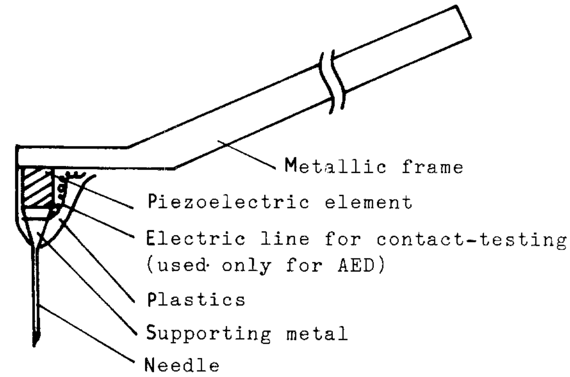

Figure 3 Structures of AED and AER.

compact bone in alveolar bone of man and dog. The implants are 10.5 mm in length, 2 mm in maximum inner diameter and 4 mm in maximum outer diameter. We can see a clear difference between non-rigid and rigid interfacial states from Figs 6a and b. The signal (c) corresponds to an interface model of good fit immediately after implantation.

Fig. 6d is a signal from the bone. Its amplitude is quite small as compared with that of Fig. 5c. This is because the sample is much thicker in Fig. 6d than in Fig. 5c.

3.3. Glass rod bonded to cattle bone with EAd and with SAd

Figs 7a to f are the signals taken from a glass rod of 16 mm × 5.5 mm × 5 mm which is partly fixed to cattle bone with EAd. The signals of Figs 7a to d show a clear difference between the bonded part and the non-bonded part of the rod. However, the signals (Figs 7e and f) taken in the directions (e) and (f) have no difference; according to them, the interface between glass and bone is rigid.

Figs 8a to c are the signals of the above rod bonded to the above bone with SAd. We see some difference in frequency and amplitude between these signals; this is partly due to some scattering in the pressure of the AED and AER upon the rod. However, all the signals clearly show that the interface is non-rigid in comparison with Figs 7a to f.

3.4. Ceramic plate bonded to cattle bone with EAd

Figs 9a to f are the signals taken from a ceramic plate, 32 mm diameter and 1.5 mm thickness, which is partly fixed to cattle bone with EAd. They show a clear difference between the bonded regions (a, b, c) and the non-bonded regions (d, e, f) of the plate.

3.5. Metal tubes in cattle bone

Fig. 10a is the signal of an aluminium alloy tube pushed into a hole of about 3.8 mm diameter and 12 mm depth in cattle bone; its compact bone is about 1 mm thickness, thinner than that in the alveolar bone of a normal adult person and mature dog. The tube, which is a dental implant model, is 20 mm length, 2 mm inner diameter and 3.8 mm outer diameter. The fixing was very tight. Fig. 10a′ is the signal obtained by pouring CAd into the gap, though invisible, of the implant–bone periphery. Fig. 10b is the signal taken from a second tube which was pushed into a same-sized hole as above and wholly bonded to the surrounding bone with EAd. Fig. 10c is the signal of another tube in a hole, about 4 mm diameter and 12 mm depth, in the same bone. The fixing seemed to be loose as judged by finger contact. The signal confirms that the interface is non-rigid.

3.6. Plastic rods and metal tubes in cattle bone

Figs 11a to d are the signals taken from acrylic resin rods and aluminium alloy tubes. The lower parts of them are fixed to holes, 4 mm diameter and 12 mm depth, in cattle bone with EAd and with SAd. The thickness of the compact bone is about 1 mm.

The rods are 12 mm length and 3.8 mm diameter for the lower part and 7 mm length and 7 mm diameter for the upper part. We can see a clear difference between the signals (a) and (b).

The tubes are of the same size as in Section 3.5. We

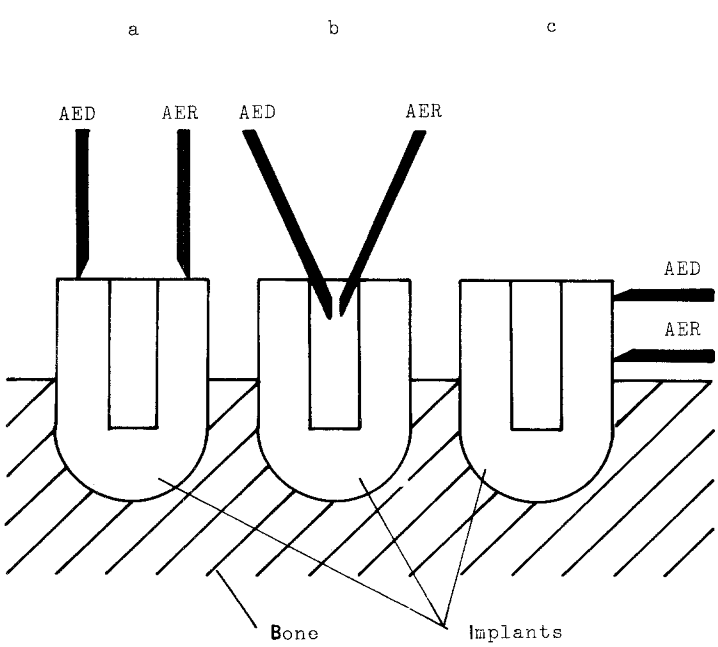

Figure 4 Geometry between AED, AER and implant.

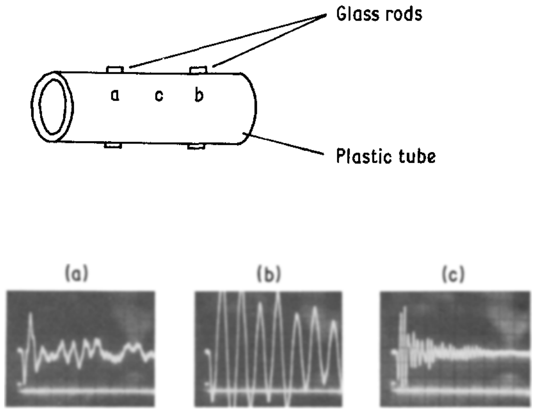

Figure 5 Signals from glass rods in a plastic tube: (a) EAd, Model b1 (see text); (b) SAd, Model c1; (c) tube.

can see a clear difference between the signals (c) and (d). However, the former's period is a little greater than that of Fig. 10b. This is because EAd is a little softer than bone.

3.7. Hollow metal rods fixed to plastic plates

If an implant was embedded in a flat bone that consisted only of a thin compact bone, what would the resulting signal be? A polyvinyl chloride (PVC) plate was used as a model of such a bone.

Figs 12a to d are the signals taken from hollow aluminium alloy rods of 12 mm length and 4 mm diameter. Each rod is bonded to a PVC plate of 3 mm thickness with EAd at a position 1 to 4 mm down from the top surface. The plate is bonded with EAd to a metal block of 20 mm thickness having holes of 30, 20, 10 and 5 mm diameter. We see that the amplitude and frequency of the signal obtained are dependent on the corresponding hole size.

Figs 13a to d are the corresponding signals taken from the same rods which are bonded to another PVC plate with SAd. In this case, the signal appears to be independent of the hole size.

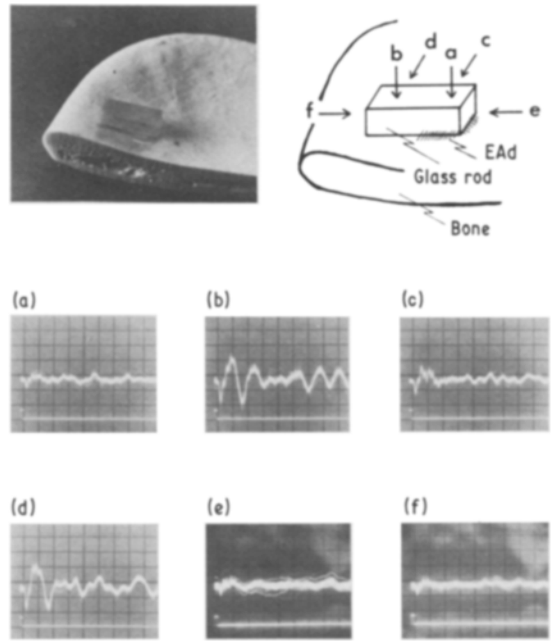

Figure 7 Signals from a glass rod partly fixed to cattle bone with EAd.

Fig. 13f is the signal taken from the same rod which was screwed on the same plate above the hole of 30 mm diameter. The fixing was tight as judged by finger contact. The signal is almost the same as that of Fig. 12a.

It should be noted that the signal amplitudes of Figs 12a and 13f are very large. However, they are smaller than that of Fig. 13a.

3.8. Metal and plastic plates on a plastic plate

Figs 14a to e are the signals taken from a PVC plate of 3 mm thickness. The plate is bonded with EAd to a metal block of 20 mm thickness having holes of 30, 20,

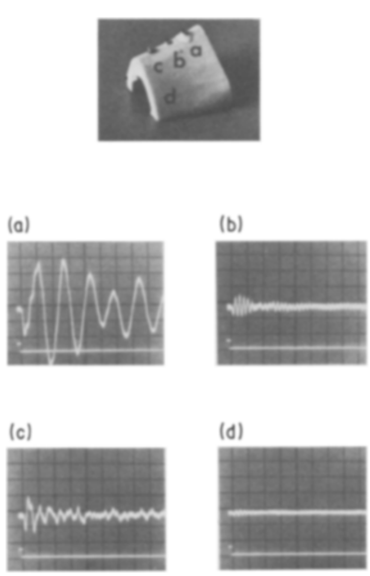

Figure 6 Signals from bioactive glass (BG)-coated metal root implants in cattle bone: (a) SAd, Model c1; (b) CAd, Model a1; (c) close contact, Model b4; (d) bone.

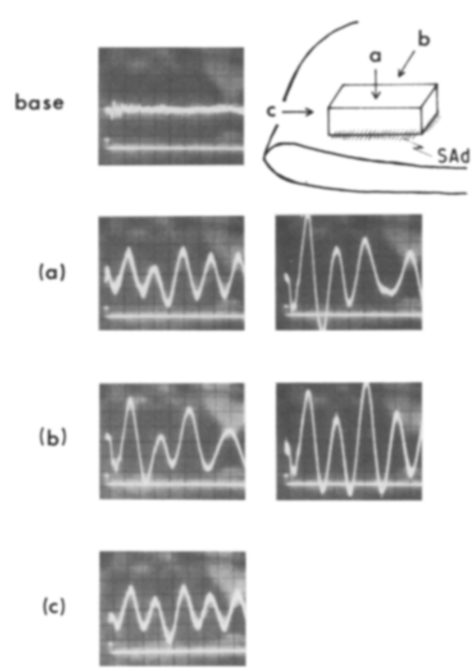

Figure 8 Signals from a glass rod bonded to cattle bone with SAd.

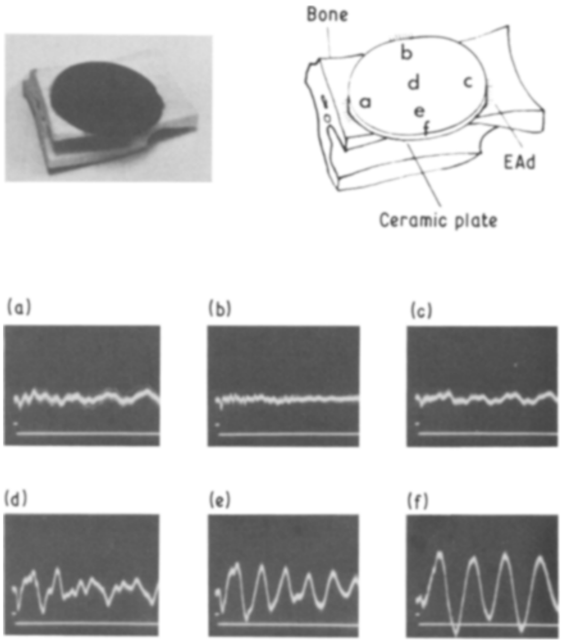

Figure 9 Signals from a ceramic plate partly fixed to cattle bone with EAd.

10, 5 and 3 mm diameter. Each signal was taken at the central region of the corresponding hole, where the amplitude was a maximum. We can see that the signal frequency is dependent on the hole size.

Fig. 15 shows the signals taken from plates of aluminium alloy and acrylic resin of 20 mm × 5 mm × 2 mm. For the signals (a), (c), (d) and (f) each plate was laid on the above PVC plate with a layer of water. We see that the signals (a) and (c) are almost the same as those of Figs 12a and 14a, respectively. For the signals (b) and (e) the metal plate was bonded to the PVC plate with CAd. The former's amplitude is smaller than that of the signal (a). This is because the CAd layer's interface is more rigid than that of the water layer.

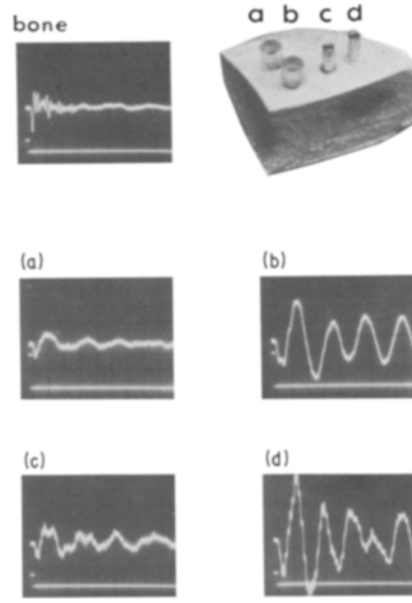

Figure 11 Signals from plastic rods and metal tubes in cattle bone: (a, c) EAd, Model b1; (b, d) SAd, Model c1.

3.9. Glass plates and metal rod on a glass block

If an implant is not bonded with bone but just closely contacted with it, what would the resulting signal be? An optically flat glass block of 50 mm diameter and 20 mm thickness was used in place of bone. The implant models used were glass plates and a steel rod; the plates were 35 mm diameter, 3.5 mm thickness (Figs 16a and c) and 49 mm diameter, 2 mm thickness (Figs 16b and d) and the rod was 5 mm length and 4 mm diameter (Figs 17a to e).

The plates were, first, just laid on the glass block (Figs 16a and b). Next, they were laid on it with a layer of water (Figs 16c and d). Judging from the latter signals, they appear not to vibrate substantially.

The rod was, first, laid on the glass block with and

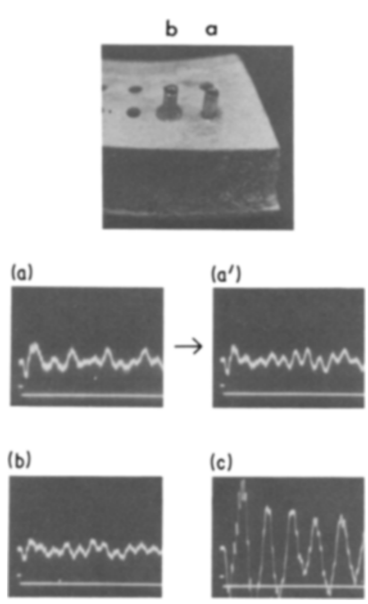

Figure 10 Signals from metal tubes in cattle bone: (a) tightly fixed, Model b5; (a′) CAd, Model b1, 5; (b) EAd, Model b1; (c) loosely fixed, Model c2.

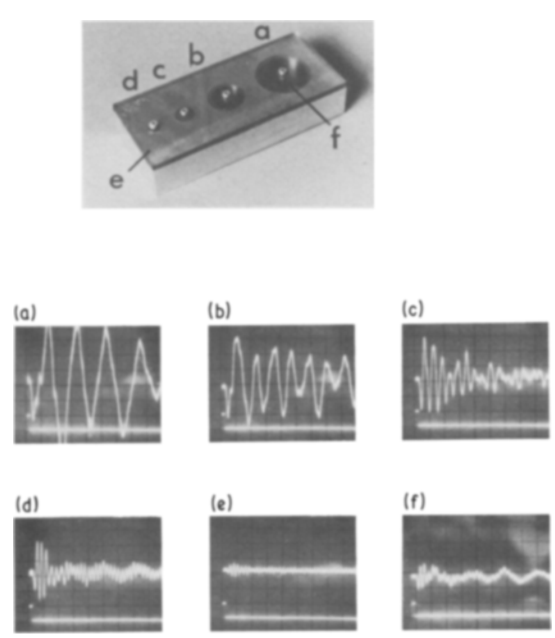

Figure 12 (a–d) Signals from metal rods bonded to a plastic plate with EAd; (e, f) signals from base.

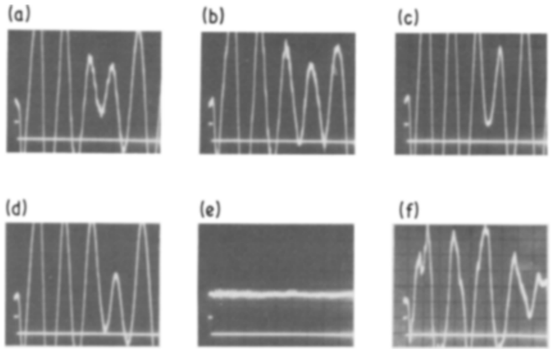

Figure 13 Signals from metal rods (a–d) bonded to a plastic plate with SAd and (f) mechanically fixed to it, Model b5 (hole diameter 30 mm); (e) signal from base.

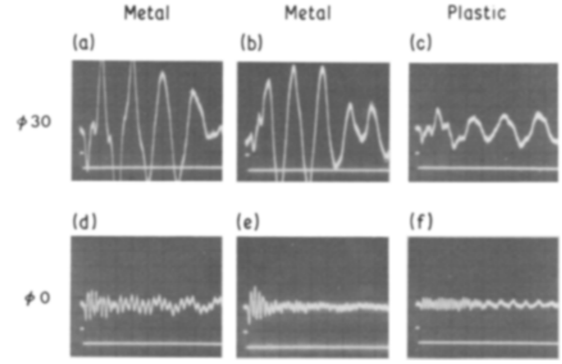

Figure 15 Signals from metal and plastic plates on a plastic plate: (a, c, d, f) with water layer, Model a2; (b, e) CAd, Model a1.

without a layer of water (Figs 17a and b). Then, one or more sheets of paper 10 μm thick, with and without water, were inserted between them (Figs 17c to e).

Figs 16 and 17 show that the water layer has a considerable effect on the interfacial rigidity.

3.10. BG-coated metal root implants fixed to plastic blocks

Fig. 18a is a signal taken from a block of epoxy resin, the thickness of which is 6 to 16 mm. The thickness variation had no significant effect on the signal.

Figs 18b to f are the signals taken from implants (see Section 3.2) the lower sides of which were fixed to the block with EAd. The signals (A) and (B) were taken in the ways shown by Figs 4a and b, respectively. Stable signals were not obtained in the latter way. However, we can see clearer differences in interfacial rigidity between the samples (b) to (f) in that way. There is a great difference between the signals (A) and (B) for the implant (b). That is, according to the former, the interface is slightly rigid, while according to the latter, it is almost non-rigid. This suggests that for an implant partly bonded or united with bone the interfacial rigidity depends on the measured direction. For the implant (f), which is almost completely bonded with the resin block, there is no significant

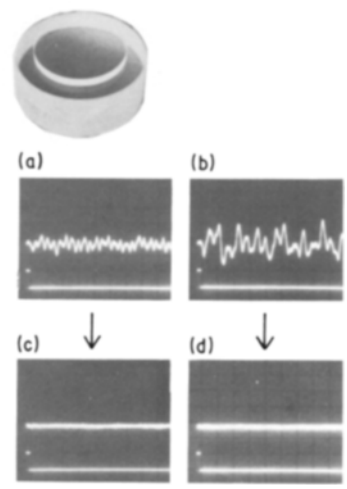

Figure 16 Signals from glass plates on a glass block: (a, b) close contact, Model b4; (c, d) with water layer, Model a2.

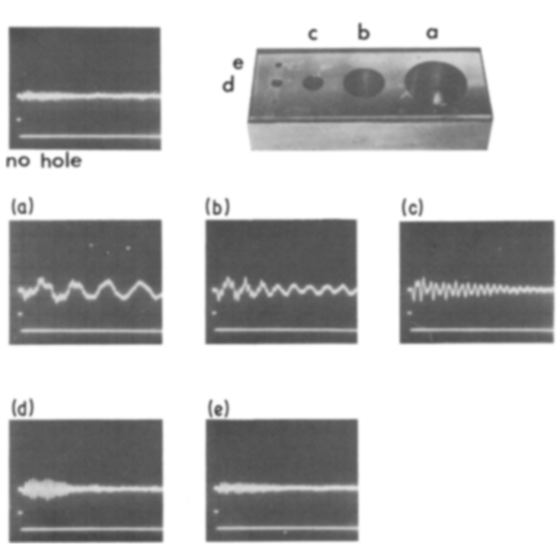

Figure 14 Signals from a plastic plate.

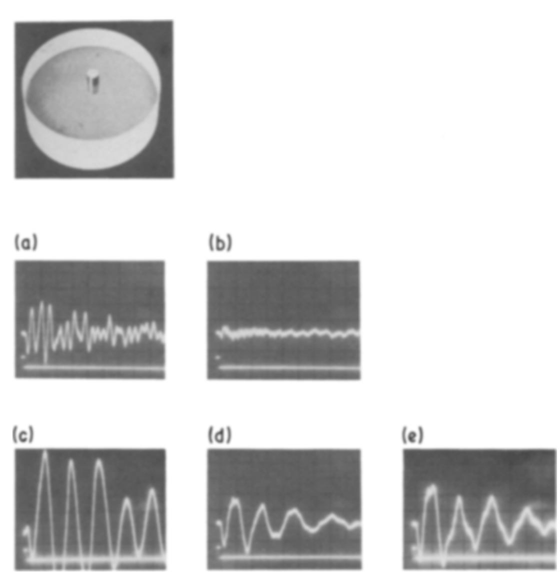

Figure 17 Signals from a metal rod on a glass block: (a) close contact, Model b4; (b) water, Model b3; (c) paper, ~10 μm; (d) water-containing paper, ~10 μm; (e) water-containing paper, ~40 μm.

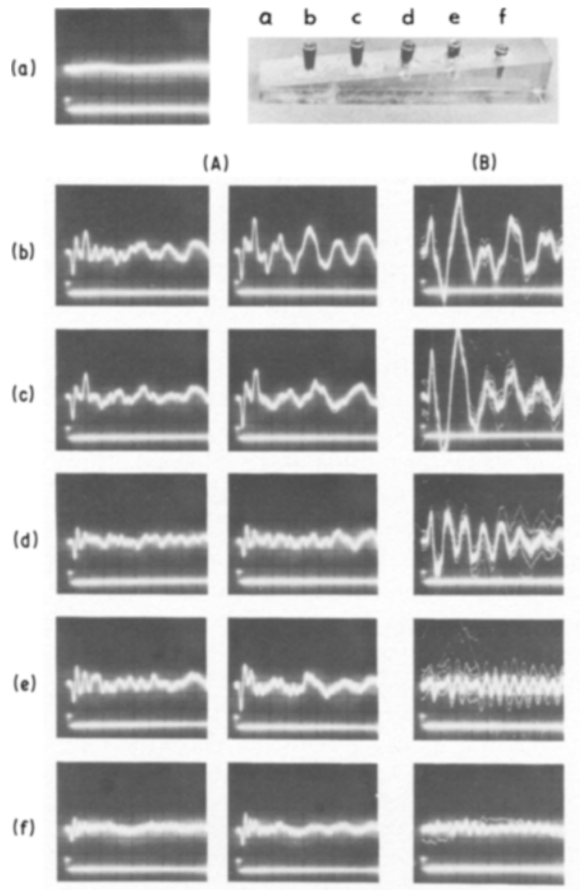

Figure 18 Signals from BG-coated metal root implants fixed to a plastic block with EAd: (A, B) taken as in Figs 4a and b, respectively.

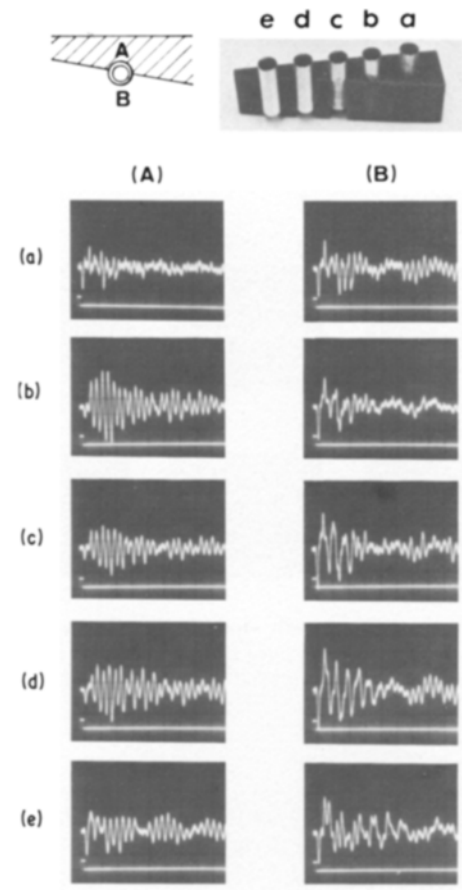

Figure 20 Signals from metal tubes fixed to a plastic block with EAd.

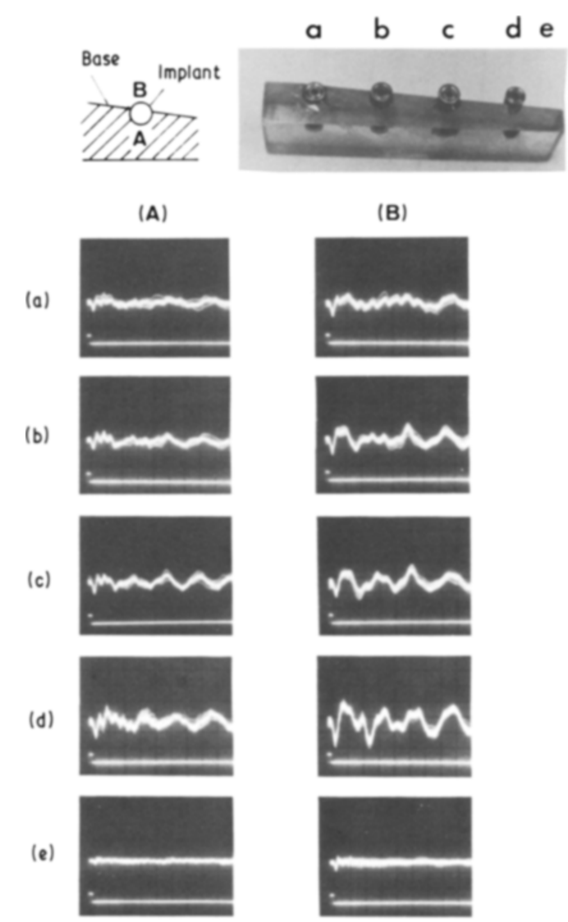

Figure 19 Signals from BG-coated metal root implants fixed to a plastic block with EAd.

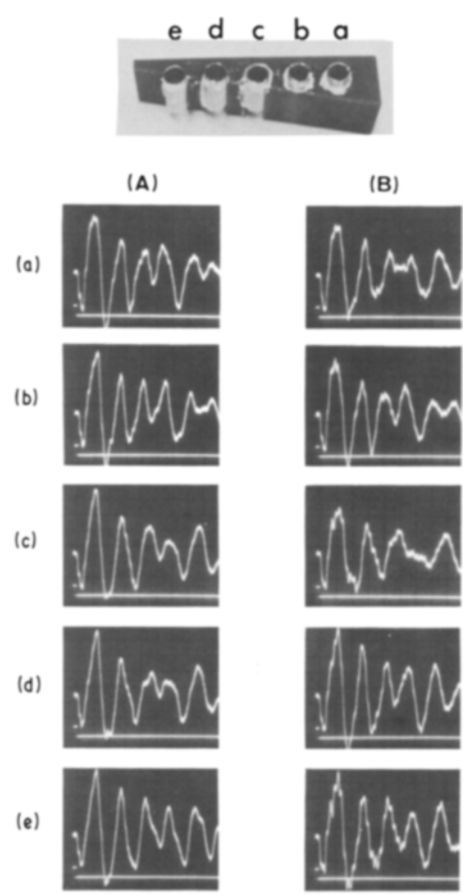

Figure 21 Signals from metal tubes fixed to a plastic block with SAd.

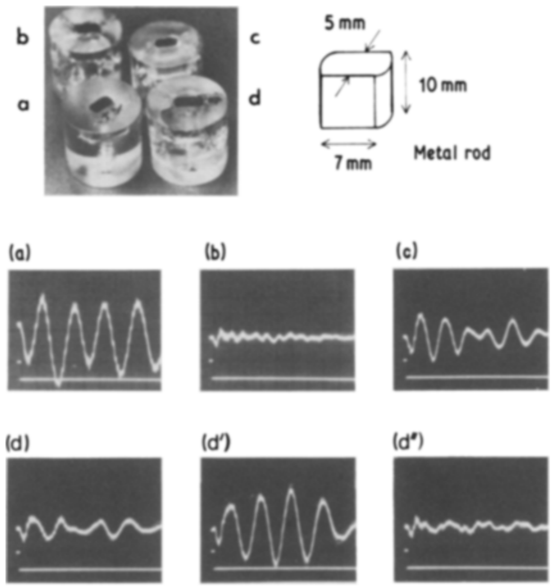

Figure 22 Signals from metal rods in plastic blocks: (a) loose mechanical fixing, Model c2; (b) EAd, Model a1; (c), SAd, Model c1; (d-, d″) EAd, Model b1, (d, d′) non-bonded side; (d″) bonded side.

difference between the signals (A) and (B); according to them, the interface is rigid.

Figs 19a to d are the signals taken from implants which are fixed to another block of epoxy resin with EAd; the thickness of it is 17 mm. The implants are about 10 mm in length, 2 mm in maximum inner diameter and 5 mm in maximum outer diameter. The signals were taken at the inner place (A) and the outer place (B) on the top surface of each implant. We can see rigidity differences between the samples (a) to (d) more clearly from (B) than from (A).

The signal amplitudes of Figs 6b, 18A and 19 are much smaller than that of Fig. 6a. The former corresponds to rigid and slightly rigid interfacial states, while the latter corresponds to a non-rigid interfacial state. This suggests that the interfacial state of a BG-coated metal root implant not united with bone will be detectable in the manner of Fig. 4a. It is confirmed by the empirical fact from the clinical test of the implant [16].

3.11. Metal tubes bonded to plastic blocks with EAd and SAd

Figs 20a to e (Figs 21a to e) are the signals taken from aluminium alloy tubes the outer sides of which are fixed to a block of phenolic resin with EAd (with SAd). The tubes are 20(15) mm length, 4.5 mm inner diameter and 5.5 mm outer diameter. The signals were taken at the inner place (A) and the outer place (B) on the top surface of each tube. There is a great difference between the signals of Figs 20 and 21. However, there are no apparent differences between the signals (a) to (e) of each figure.

3.12. Metal rods in plastic blocks

Figs 22a to d show the signals of copper alloy rods embedded in acrylic resin blocks. For (d), only the right side of the rod is bonded with EAd. The signals from it show a clear difference between the bonded part and the non-bonded part.

4. Conclusion

Ex vivo results have shown that the acoustoelectric technique is applicable to the assessment of the interfacial states for various bone implants. However, it has been found that the signal taken from an implant depends on the surrounding bone and the implant material as well. Therefore, the *in vivo* assessment for an implant by this technique should always be done together with the corresponding *ex vivo* assessment.

References

1. U. GROSS, J. BRANDES, V. STRUNZ, I. BAB and J. SELA, *J. Biomed. Mater. Res.* **15** (1981) 291.
2. J. WILSON, in "Glass", edited by A. F. Wright and J. Dupuy (Nijhoff, Boston, 1985) p. 662.
3. P. DUCHEYNE, *J. Biomed. Mater. Res.* **19** (1985) 273.
4. W. HÖLAND, W. VOGEL, K. NAUMANN and J. GUMMEL, *ibid.* **19** (1985) 303.
5. T. NAKAMURA, T. YAMAMURO, S. HIGASHI, T. KOKUBO and S. ITOO, *ibid.* **19** (1985) 685.
6. W. R. LACEFIELD and L. L. HENCH, *Biomaterials* **7** (1986) 104.
7. H. KAWAHARA and T. MAEDA, *Saibo* **16** (1984) 120.
8. Y. AKAGAWA, M. HASHIMOTO, N. KONDO, T. MATSUMOTO, Y. MORIUE, H. TAMAGAWA, T. SATO and H. TSURU, *J. Jpn. Prostho. Soc.* **28** (1984) 810.
9. P. J. ATKINSON, B. B. SEEDHOM and E. W. ROBERTS, *Biomaterials* **6** (1985) 75.
10. H. W. DENISSEN, A. A. H. VELDHUIS, H. W. B. JANSEN and A. van den HOOFF, *J. Biomed. Mater. Res.* **18** (1984) 147.
11. C. A. van BLITTERSWIJK, J. J. GROTE, W. KUIJPERS, W. TH. DAEMS and K. de GROOT, *Biomaterials* **7** (1986) 137.
12. P. -I. BRÅNEMARK, *J. Prosthet. Dent.* **50** (1983) 399.
13. T. ALBREKTSSON, H. -A. HANSSON and B. IVARSSON, *Biomaterials* **6** (1985) 97.
14. K. A. THOMAS, S. D. COOK, E. A. RENZ, R. C. ANDERSON, R. J. HADDAD Jr, A. D. HAUBOLD and R. YAPP, *J. Biomed. Mater. Res.* **19** (1985) 145.
15. T. KANEKO, Y. NAGAI, M. OGINO, T. FUTAMI and T. ICHIMURA, *ibid.* **20** (1986) 169.
16. M. MIYASAWA, K. KUDO, Y. FUJIOKA, T. SHIOYAMA, K. NAKANO, Y. SEINO and T. KANEKO, Annual Meeting of the Japanese Stomatological Society, Fukuoka, May 1986.

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