An *in vitro* study into the corrosion of intra-oral magnets in the presence of dental amalgam

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SUMMARY The aim of this investigation was to study the corrosion behaviour and products of uncoated neodymium–iron–boron magnets in the presence of dental amalgam. Microcosm plaques were grown on discs of neodymium–iron–boron magnets or amalgam in a constant depth film fermentor. The biofilms were supplied with artificial saliva and growth was determined by viable counting.

The results showed that the neodymium–iron–boron magnets corroded with an average daily weight loss of 0.115 ± 0.032 per cent. However, when the magnets were in close proximity to the amalgam the amount of corrosion was reduced to a daily loss of 0.066 ± 0.023 per cent. The highest loss of constituent elements from the corrosion products of the magnets was observed for iron. The composition of the microcosm plaques altered markedly between the two materials with less streptococci and more *Veillonella* spp. present in the biofilms grown on magnets in the presence of amalgam. The corrosion of neodymium–iron–boron magnets is limited and in the presence of amalgam is reduced further. This suggests that amalgam present in the mouth will not cause an increased clinical risk in terms of biocompatibility with neodymium–iron–boron magnets.

Introduction

Magnets have been used in orthodontics in many applications and have several advantages over traditional force delivery systems. It is, however, recognized that rare earth magnets and in particular neodymium–iron–boron are susceptible to corrosion, with the release of potentially harmful products (Noar and Evans, 1999). Dental amalgam has been used as a tooth restorative material for almost 150 years. Jones (1994) estimated that about 100–200 million North Americans have oral amalgam restorations, and these restorations account for 75–80 per cent of all single-tooth fillings in this population.

Dental plaque is a multi-species biofilm found on non-shedding surfaces of the mouth. A biofilm has been defined as 'a community of bacteria (or other microbes) and their extracellular polymers that is attached to a surface' (Wilson, 2001). Biofilm formation on metal surfaces combined with a high water content generated from saliva produces an ideal environment for the process of corrosion in the mouth. These large aggregates of bacteria form local cathodes or anodes, which result in a corrosion current. Additionally, the metabolic activity of the bacteria can lead to the accumulation of acids that can enhance corrosion.

The aim of this *in vitro* investigation was to study the corrosive behaviour of intra-oral magnets in the presence of amalgam.

Materials and method

Substratum

The magnets used in this investigation contained mainly iron, neodymium and boron together with traces of dysprosium and aluminium ($Nd_2Fe_{14}B$; Magnet Development Ltd, Swindon, Wilts, UK). These were magnetized at source and subsequently demagnetized by heating to 320°C to enable insertion into the constant depth film fermentor (CDFF; University of Wales, Cardiff, UK) (Figure 1). Dispersalloy amalgam (Dentsply Caulk, Milford, DE, USA) was also used in the experiments. Both materials were handled with gloves to avoid any contamination with skin secretions.

Production of biofilms

Human saliva was used as an inoculum to provide a multi-species biofilm consisting of organisms found in the oral cavity. The saliva was collected from 10 healthy individuals. An equal volume from each of the subjects was pooled and aliquots of 1 ml were stored at –80°C for subsequent use.

Biofilms were grown in the CDFF, a model which has been used previously to investigate factors that may influence the growth of bacterial communities in the oral ecosystem (Wilson, 1999). Briefly, the CDFF comprises a stainless steel turntable, which rotates under polytetrafluoroethylene (PTFE) scraper blades.
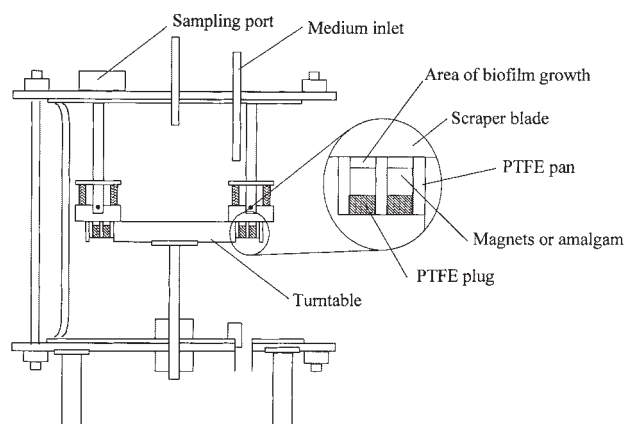
Figure 1 A schematic of a vertical section through the constant depth film fermentor showing one of the 15 polytetrafluoroethylene (PTFE) pans in detail.

The turntable holds 15 PTFE pans flush around its rim, each having five vertical holes containing 5 mm diameter PTFE plugs. The biofilms were grown on magnet or amalgam discs, 5 mm in diameter and 1 mm in depth, which sit on the plugs and are recessed 300 µm below the height of the pan. Media and nutrients enter through a stainless steel plate at the top of the fermentor, which also has an air inlet and a sample port, while the base plate has an effluent outlet. The nutrient source for the experiments was a mucin-containing artificial saliva, the composition of which has been described previously (Pratten *et al.*, 1998).

One millilitre of the pooled saliva was added to 500 ml of artificial saliva. This was mixed and pumped into the CDFF for 8 hours. After this time, the inoculation vessel was disconnected and the medium reservoir containing sterile artificial saliva was connected to the CDFF. The artificial saliva was delivered via a peristaltic pump (Watson-Marlow, Falmouth, Cornwall, UK) at a rate of 0.72 l per day, corresponding to the resting salivary flow rate in man (Lamb *et al.*, 1991).

Culture methods

Pans containing five biofilms were removed from the CDFF and the magnets and amalgam placed into separate vials containing 1 ml of phosphate-buffered saline (PBS), before being vortexed for 1 minute to disrupt the biofilm. Selective media were used to culture the following genera; *Actinomyces* spp. were isolated on cadmium fluoride/acriflavin/tellurite agar plates (Zylber and Jordan, 1982), *Veillonella* spp. on Veillonella agar (Difco Laboratories, Detroit, MI, USA) and streptococci on Mitis Salivarius agar (Difco). The total anaerobic count was performed on Wilkins-Chalgren agar (Oxoid, Basingstoke, Hants, UK) containing 8 per cent horse blood. All the plates were incubated anaerobically for

4 days at 37°C. The total aerobic viable counts were carried out on 8 per cent blood agar (Oxoid) and incubated at 37°C aerobically. The magnets were then removed from the vials, dried and weighed and the corrosion products that remained in the vials were spun at 13 000 g for 10 minutes.

Electron microscopy

For scanning electron microscopy the magnets were air dried and placed in a desiccator. After 7 days they were removed and mounted on to aluminium stubs using epoxy resin (Araldite), ensuring that the surface of interest was uppermost. The specimens were sputter coated with gold/palladium in a Polaron E5100 sputter coater (Bio-Rad, East Grinstead, West Sussex, UK) and were then viewed on a Cambridge Stereoscan 90B (Cambridge, UK) electron microscope operating at 15 kV.

Analysis of corrosion products

To process the corrosion products, 4 ml of 4 per cent nitric acid (Sigma, Poole, Dorset, UK) was added to the 1 ml of PBS containing the magnets in order to dissolve the products. The median weight of the sample was determined in each case. The constituents of the corrosion products were investigated using inductively coupled plasma atomic emission spectrometry (ICP-AES; Philips, Croydon, Surrey, UK, PV8050 simultaneous/sequential ICP-AES).

Results

The total aerobic and anaerobic viable counts from biofilms grown on magnets alone and on magnets in the presence of amalgam showed very similar values. At 24 hours all the counts were between 7.3×10^6 and 2×10^7 colony forming units, while after 20 days' growth the viable counts varied by less than 1 $\log_{10}$.

The proportions of the three genera investigated were within the range expected for approximal dental plaque (Table 1). However, differences were observed in the percentage of genera present in biofilms grown on the different substrata. Biofilms grown on magnets in the absence of amalgam had a high mean percentage of *Streptococcus* spp. and very low proportions of *Veillonella* spp. In contrast, the *Actinomyces* spp. were the predominant genera when the biofilms were grown on magnets in the presence of amalgam (increase of 9 per cent) with a greater proportion of *Veillonella* spp. also present (an increase from 1 to 18 per cent).

The weight loss of the magnets over the course of the experiment is shown in Figure 2. There was a greater percentage weight loss of the magnets in the absence of amalgam. At 600 hours, the final sample point, there

Table 1 Comparison of the bacterial composition of approximal dental plaque (Marsh and Martin, 1999), pooled human saliva used as the inoculum and the microcosm plaques grown on magnets and on magnets in the presence of amalgam. The data represent the proportion of each type of organism expressed as a percentage of the total anaerobic viable count. Means and ranges are from four runs.

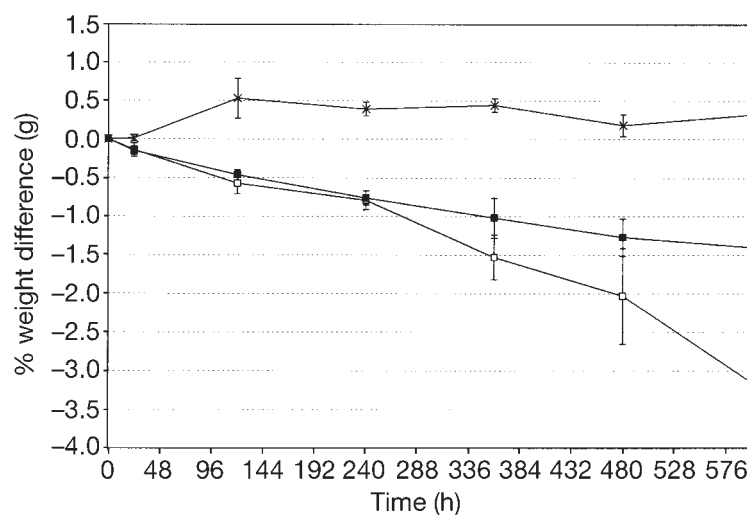| Genera	Pooled human saliva		Approximal dental plaque		Magnets		Magnets + amalgam	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Actinomyces spp.	7	1–16	42	4–81	29	13–40	38	21–45
Streptococcus spp.	86	47–92	23	0.4–70	37	11–60	18	10–35
Veillonella spp.	4	1–14	13	0–59	1	0.3–1.3	18	16–20

Figure 2 Percentage weight loss of magnets (□), magnets in the presence of amalgam (■) and amalgam (×).

was a significant (1.75 per cent; $P < 0.05$) weight difference between the magnets in the absence and presence of amalgam. At the same sampling times the percentage weight of amalgam increased, although after 120 hours this did not seem to correlate with any weight loss from the magnets.

The elements comprising the corrosion products were also investigated. ICP-AES showed a significant loss of neodymium, iron and dysprosium (Figure 3). The greatest weight loss was observed for iron (0.0058 g) and neodymium (0.0025 g) from magnets alone at 600 hours. The same trend was observed for the magnets in the presence of amalgam, although the weight loss was considerably reduced (a total weight loss of 0.0037 g). There was no weight loss observed for either boron or aluminium (results not shown).

The magnet surfaces after 480 hours' exposure to the microcosm biofilms in a CDFF experiment without and with amalgam are shown in Figure 4a and b, respectively. It can be seen that in the different environments the corrosive behaviour of the materials is altered. Figure 4a shows a corroded surface with deposition of corrosion products. However, the magnets which had corroded in

the presence of amalgam had deep crevices on their surface with less corrosion products visible.

Discussion

The corrosion of intra-oral magnets is influenced by chemical, mechanical and biological factors and this has been a cause for concern because of the potential effect on the mechanical properties of the magnets and the possible release of toxic corrosion products. This study focused on the corrosion of neodymium–iron–boron magnets in the presence of amalgam.

The magnets used were uncoated demagnetized neodymium–iron–boron magnets. For clinical use these are normally coated to prevent corrosion (Wilson *et al.*, 1995). However, it has been previously shown that this coating is weak and, under occlusal forces, can be breached (Noar *et al.*, 1999). These magnets were without a coating to represent the worst possible case for corrosion in the clinical situation.

Corrosion is divided into different stages (Tokuhura and Hirosawa, 1991). Initially, neodymium diffuses across the neodymium-rich grain boundaries of the magnets
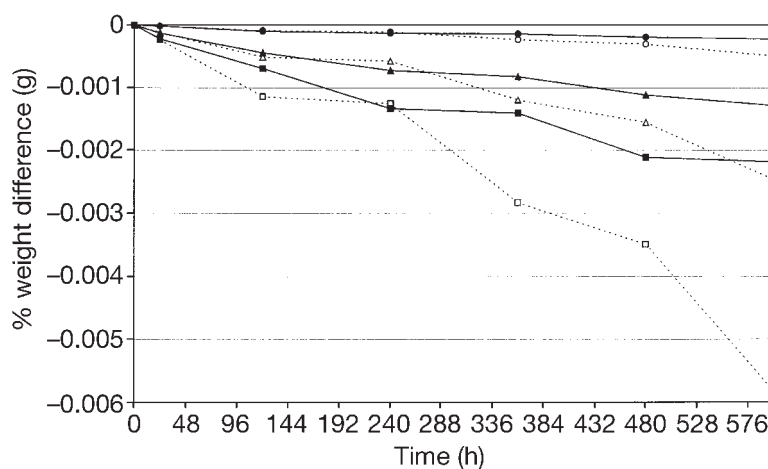
Figure 3 Elemental weight loss, as determined by inductively coupled plasma atomic emission spectrometry, of iron from magnets (□) and magnets in the presence of amalgam (■), of neodymium from magnets (△) and magnets in the presence of amalgam (▲) and of dysprosium from magnets (○) and magnets in the presence of amalgam (●).
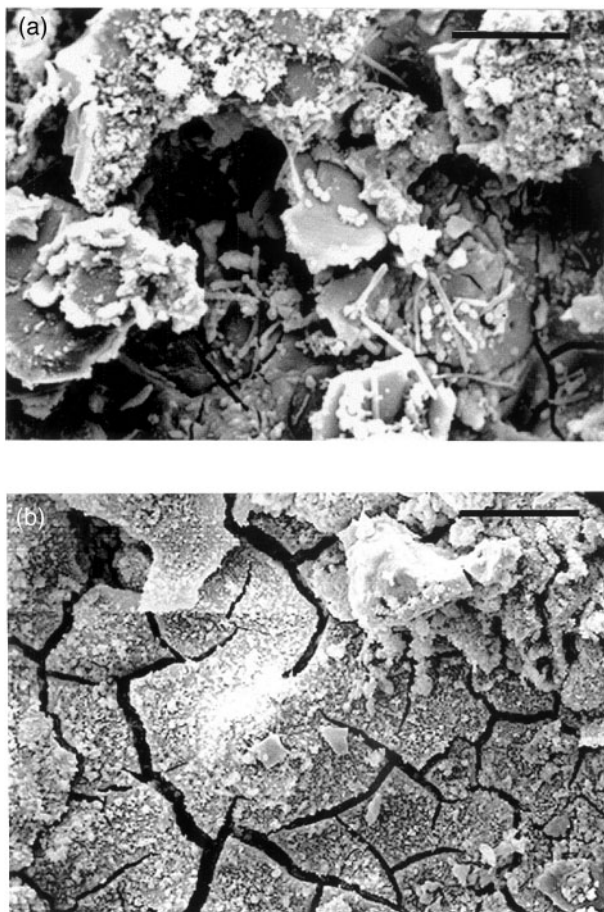

Figure 4 Electron micrographs of (a) the magnet surface and (b) the magnet surface in the presence of amalgam, after 480 hours' exposure to microcosm biofilms. Bar = 20 μm.

reacting with moisture to form either neodymium oxides or hydroxides at the surface. Upon further corrosion, the brittle neodymium–iron–boron compounds are formed, and these appear as lumps of oxide or hydroxides of neodymium and iron on the surface. Finally, the corrosion process proceeds deeper into the magnets, forming mostly iron oxides or hydroxides. The result of these processes is that ions of neodymium and iron, in the form of their oxides and hydroxides, are released into the environment. Why the amalgam appears to gain weight is unclear. However, it does not seem to be directly related to the linear weight loss of the magnets.

Whether the reduction in corrosion in the presence of amalgam is due to the amalgam producing materials that can be cytotoxic to the biofilm, thereby reducing the corrosive property of it, or whether oxides or hydroxides are deposited on the magnets through the electrochemical cell formed between the two dissimilar metals, is not known.

A carious lesion will result from the demineralization of tooth enamel due to acids, in particular lactic acid, produced from the microbial fermentation of dietary carbohydrates (Hazen *et al.*, 1973; Mikx and van der Hoeven, 1975). Hence, the decreased number of streptococci in the biofilms grown on magnets in the presence of amalgam implies that they would be less cariogenic than the biofilms grown on magnets alone. The presence of higher proportions of *Veillonella* spp. in plaque is also considered to be an indication of a reduced cariogenic potential, as these organisms use lactate as a carbon and energy source and convert it to propionic acid which is a much weaker acid (Minah *et al.*, 1981). Although caries will not occur on the magnets themselves, the enamel in close proximity may be susceptible to a more cariogenic bacterial population.

Conclusions

The results of this study show that the corrosion of neodymium–iron–boron magnets is limited and in the presence of amalgam is reduced further. This suggests that there is no reason that amalgam present in the mouth will cause an increased clinical risk in terms of biocompatibility when using neodymium–iron–boron magnets. The effects of those corrosion products released into the oral environment, however, have not been assessed and therefore the safety of using rare earth neodymium–iron–boron magnets cannot be absolutely confirmed.

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Acknowledgements

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