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Continuous forces are more effective than intermittent forces in expanding sutures

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SUMMARY While both intermittent and continuous forces are commonly used to expand sutures, it remains unclear which force is most effective. Using nickel-titanium (NiTi) open coil springs (50 g) and 3 mm long miniscrew implants (MSIs) for skeletal anchorage, intermittent and continuous forces were used to expand the midsagittal sutures in 18 New Zealand white juvenile male rabbits, 11 weeks of age, for 29 days. In the intermittent group, expansion forces of 50 g were delivered for 5 days (on) and paused for 1 day (off); the on/off cycles were repeated five times. Expansion forces of 50 g were delivered for 29 consecutive days in the continuous group. Longitudinal biometric and histomorphometric analyses were performed to evaluate sutural separation and bone formation using implanted tantalum bone markers and fluorescent bone labelling, respectively. Multilevel modelling procedures were undertaken to compare the groups and time intervals.

Continuous forces produced significantly greater overall sutural separation (1.3 mm) than intermittent forces (0.8 mm). Although they were delivered over a period of time 86 per cent as long, intermittent forces produced only 61 per cent of the sutural separation of continuous forces. Between days 7 and 17, continuous forces resulted in significantly greater mineral apposition and bone formation rates than intermittent forces. Intermittent forces produced approximately 59 per cent as much mineral apposition and 61 per cent as much bone formation as continuous forces. Due to greater sutural separation and bone formation, continuous forces provide a more effective approach for separating sutures than intermittent forces.

Introduction

Both intermittent and continuous forces are routinely applied to expand sutures in patients with maxillary deficiencies. Palatal expanders, which are used by the vast majority (>96 per cent) of orthodontists (Keim *et al.*, 2002), are intermittently activated, but apply a continuous residual force across the suture during active treatment (Isaacson and Ingram, 1964). In contrast, face masks used to protract the maxilla apply intermittent forces.

While continuous (Nanda, 1978; Jackson *et al.*, 1979; Mossaz-Joëlson and Mossaz, 1989) and intermittent (Kambara, 1977) forces are both capable of separating sutures, their relative effects on sutures have not been systematically studied. Most experimental research has focused on the effects of continuous forces (Cotton, 1978; Nanda, 1978; Jackson *et al.*, 1979). Assuming the same force magnitude, continuous forces might be expected to produce more sutural separation than intermittent forces because they are maintained over a longer duration. Differences in magnitude explain why greater amounts of continuous force produce more sutural separation than lower continuous forces applied over the same time periods (Hickory and Nanda, 1987; Mörndal, 1987; Parr *et al.*, 1997). Alternatively, it is possible that intermittent forces could produce more sutural bone formation than continuous forces, because bone is a unique tissue that alters its mass as an adaptation to changes in stress and strain (Forwood and Turner, 1994;1995). Breaks or recovery periods between loadings, ranging from seconds to weeks, have been shown to increase bone formation, presumably by resuming cell sensitivities (Lanyon and Rubin, 1984; Robling *et al.*, 2001a; Srinivasan *et al.*, 2002; Saxon *et al.*, 2005). Whether or not such rest periods or breaks associated with intermittent forces, increase in bone formation has not been previously investigated.

The lack of appropriate animal models could explain why continuous and intermittent forces have not previously been compared. The experimental model should make it possible to apply the same force magnitudes continuously in one group and intermittently in the other. In order to control force magnitudes, both absolute anchorage and constant forces are required. Expansion forces applied by helical springs, for example, would not be acceptable because they dissipate rapidly during expansion (Hinrichsen and Storey, 1968; Southard and Forbes, 1988). Nickel-titanium (NiTi) open coil springs make it possible to ensure the constancy of the expansion force (Miura *et al.*, 1988; Von Fraunhofer *et al.*, 1993). Moreover, expansion forces applied to teeth are difficult to control due to reciprocal anchorage. Miniscrew implants (MSIs) provide absolute skeletal anchorage and greater control of the forces (Creekmore and Eklund, 1983; Kyung *et al.*, 2003).

Using immediately loaded MSIs and NiTi coil springs, the purpose of this study was to compare continuous or intermittent forces. The null hypotheses tested are that there are no differences in sutural separation or bone formation between these two types of forces.

Material and methods

Sample

The sample included 18, 11-week-old, juvenile male New Zealand white rabbits. The housing, care, and experimental protocol were in accordance with the guidelines set forth by the Institutional Animal Care and Use Committee. After their arrival at the facilities, all the animals were quarantined for a period of 3 days. The animals were maintained under standard laboratory conditions and were provided with a stock diet and water *ad libitum*.

Experimental design

The rabbits were randomly assigned to three groups: a continuous force (n = 7), an intermittent force (n = 7), or a control (n = 4). Expansion forces (50 g) were delivered for 29 consecutive days in the continuous force group. In the intermittent force group, a 50 g force was delivered continuously for 5 days, paused for 1 day, and then resumed for 5 days (Figure 1). The expansion/pausing cycles were repeated five times until sacrifice at day 29. Previous studies have shown that time-off as short as 10 seconds and 8 hours, or as long as 5 weeks between continuous loadings can stimulate greater bone formation in long bone (Robling *et al.*, 2001a; Srinivasan *et al.*, 2002; Saxon *et al.*, 2005). It is postulated that a 1 day time-off between continuous sutural expansion may trigger greater sutural bone formation. No forces were employed in the control group.

MSI insertion, bone marker placement, and force delivery

All animals were anaesthetized with ketamine at 75 mg/kg/im and acepromazine 5 mg/kg/im. Marcaine® 0.5 per cent with 1:200 000 epinephrine as the local anaesthetic. The surgical sites were shaved and disinfecting agents were applied. All surgical procedures were performed under sterile conditions. Two 2.0 mm diameter regions of skin were removed using a tissue punch (Miltex, York, Pennsylvania, USA) approximately 4–5 mm on either side of the midsagittal suture (inter-frontal bones) midway between the anterior and posterior limits of the orbital rims (Figures 2A, B and 3A). Pilot holes were drilled using a size 2 round bur with a low-speed handpiece (less than 600 r.p.m.) and copius saline irrigation. Two custom-made MSIs (Dentos, Seoul, Korea; thread 3.0 mm long × 1.7 mm in diameter; Figure 2C) were placed in each animal with a manual screw driver.

Two 1.5 mm long 99.95 per cent tantalum bone markers with a diameter of 8 mm were tapped into the skull 3–4 mm anterior to the MSIs using a custom-made stainless steel appliance. The bone markers were used to radiographically quantify sutural width and implant movements (Figure 3A). All animals were given penicillin (60000 IU/lb/im) immediately after surgery to prevent infection.

A 20 mm long, 0.020 inch diameter, stainless steel inter-abutment guide wire was engaged into the holes located in the MSI heads. A 15 mm long Sentalloy® NiTi open coil spring (GAC, Bohemia, New York, USA), which delivered a force of 50 g was telescoped over the wire between the two MSIs. Two stop loops were bent to prevent the spring and wire from becoming dislodged (Figure 2D, E). The forces exerted by the NiTi open coil springs were maintained because the spring remained compressed at lengths ranging from 8 to 12 mm (Von Fraunhofer *et al.*, 1993). The force levels were checked on days 5, 11, 17, 23, and 29. When necessary, sliding tubes were added to the inter-abutment guide wire to maintain the compressed length of the spring. In the intermittent force group, a 0.010 inch diameter ligature wire was ligated through the inner lumen of the NiTi open coil spring to pause the expansion forces. The force was resumed by loosening the ligature wire.

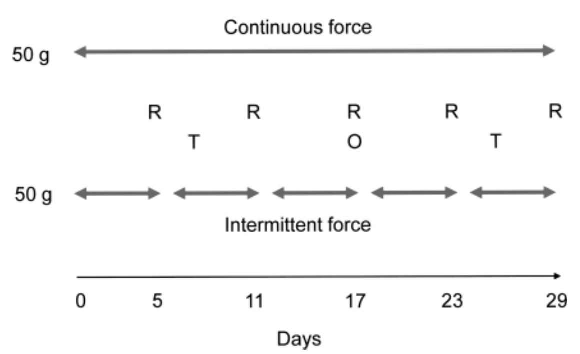

Figure 1 Experimental timeline. Expansion forces were applied over a 29 day period. They were paused four times (days 5, 11, 17, and 23) in the intermittent group. Bone labels were given at day 7 (oxytetracycline), 17 (calcein), and 27 (oxytetracycline). Records (R) were taken at days 5, 11, 17, 23, and 29.

Records

Records, including animal weights, ventrodorsal cephalometric radiographs, and digital calliper width measurements accurate to 0.01 mm (Figure 3B), were obtained under anaesthesia at six time points (Figure 1). Using a customized head holder, standardized ventrodorsal radiographs were taken at 60 kVp and 10 mA, for 12 seconds at fixed distances.

Bone labelling

To localize the bone-forming regions on the midsagittal suture, oxytetracycline (13.6 mg/lb/im; Teradura™ 300, Duluth, Minnesota, USA) and calcein (10 mg/kg/im; Sigma, St Louis, Missouri, USA) fluorescent labels were administered to all animals. Oxytetracycline was given at days 7 and 27; calcein was given at day 17 (Figure 1). It has previously been shown that advancing bone fronts during sutural expansion

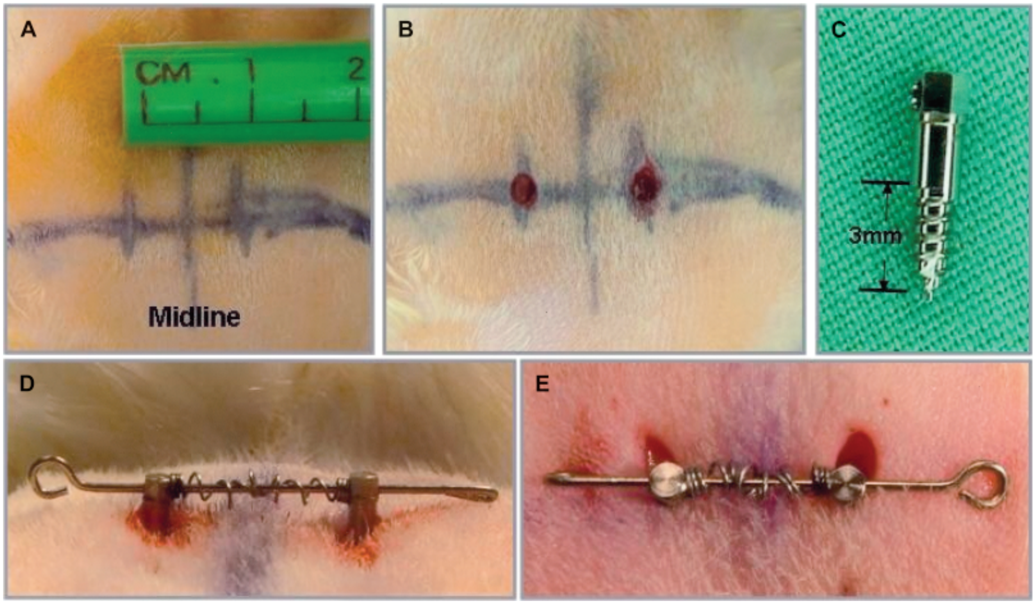

Figure 2 (**A**) Planned miniscrew implant (MSI) insertion sites, (**B**) removal of skin by tissue punch, (**C**) the 3 mm MSI used, (**D**) the expander consisting of the two MSIs, a guide wire, and a nickel-titanium open coil spring, and (**E**) superior view of the expander.

incorporate fluorescent labels, making it possible to quantify new bone formation (Parr *et al.*, 1997).

Histological preparation

After 29 days of suture expansion, the rabbits were killed using an overdose of Beuthanasia (intracardiac injection of 1 cc per animal) and perfused with 70 per cent ethanol. A standardized area, including the midsagittal region, adjacent bone, and MSIs, was dissected and fixed with 70 per cent ethanol for 7 days. The anterior region of bone was decalcified, embedded with paraffin, sectioned (6 μm) coronally, and haematoxylin and eosin (HE) stained (eight sequential sections per animal). The posterior region remained undecalcified; it was embedded along with the MSIs in polyester resin and then sectioned (approximately 60 μm) coronally using a diamond saw (four sequential sections per animal; Figure 3), followed by grinding and polishing.

Analysis

Biometric. Biometric assessments were based on the calliper and radiographic measurements. Calliper width measurements between each MSI pair were taken at the top and bottom of the outermost margins (Figure 3B). The bone markers and outermost margins of the MSI (Figure 3A) were digitized (again blinded) on the radiographs and the widths were calculated using Viewbox 3.1 (dHal, Kifissia, Greece). After 2weeks, 40 radiographs were re-measured to establish intra-examiner method error (bone marker widths: 0.10 mm; inter-MSI radiographic widths: 0.12) using Dahlberg's formula [$\sqrt{(\sum d^2/2n)}$].

Histomorphometric. AZeissAxiomicroscope (Thornwood, New York, USA) was used to examine the HE sections (n = 136) and a Nikon microscope (Melville, New York, USA) i80 epifluorescence with excitation wave lengths of 390 nm for oxytetracycline and 485 nm for calcein was used for the undecalcified sections (n = 72). Blinded with respect to the groupings, standardized measurements were performed on each of the saved images by the same investigator (SS-YL) using MetaMorph 6.3 (Molecular Devices, Sunnyvale, California, USA).

New bone formation, suture area, and overall sutural expansion (Figure 4A) were measured on the HE sections using standardized (×50) regions of interest located at the centre of the suture. New bone area was defined based on the presence of Sharpey's fibres in the bone tissue.

Widths and lengths of the fluorescent bone labels at the edges of the sutures were measured by the same blinded examiner (SS-YL). The grid and intercept method (Figure 4B) was used to calculate mineral apposition rates [MARs (μm/day) = inter-label width/number of days] and bone formation rates [BFRs (mm^2/year) = MAR × (double label length + 1/2 single label length)/365] (Parfitt *et al.*, 1987). For each image, the suture was orientated as vertical as possible and a horizontal grid was randomly displayed on the computer monitor parallel to the direction of sutural bone formation. The widest 10 inter-label widths on the grid were selected to be measured on both sides of the sutural margins. MAR was calculated based on the average of 20 measurements.

Statistical analysis

All statistical procedures were performed using the Multilevel Win 2.0 (Centre for Multilevel Modelling, University of

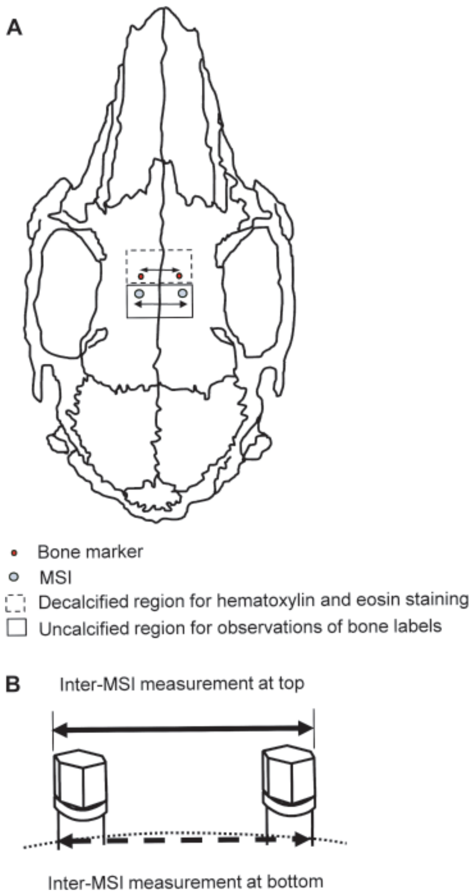

Figure 3 Illustrations showing (**A**) locations of miniscrew implants (MSIs) and bone markers, radiographic measurements of inter-MIS and inter-bone marker widths, and regions of the skull dissected for histomorphometric analysis and (**B**) calliper width measurements taken at the top and bottom outermost margins of the MSIs.

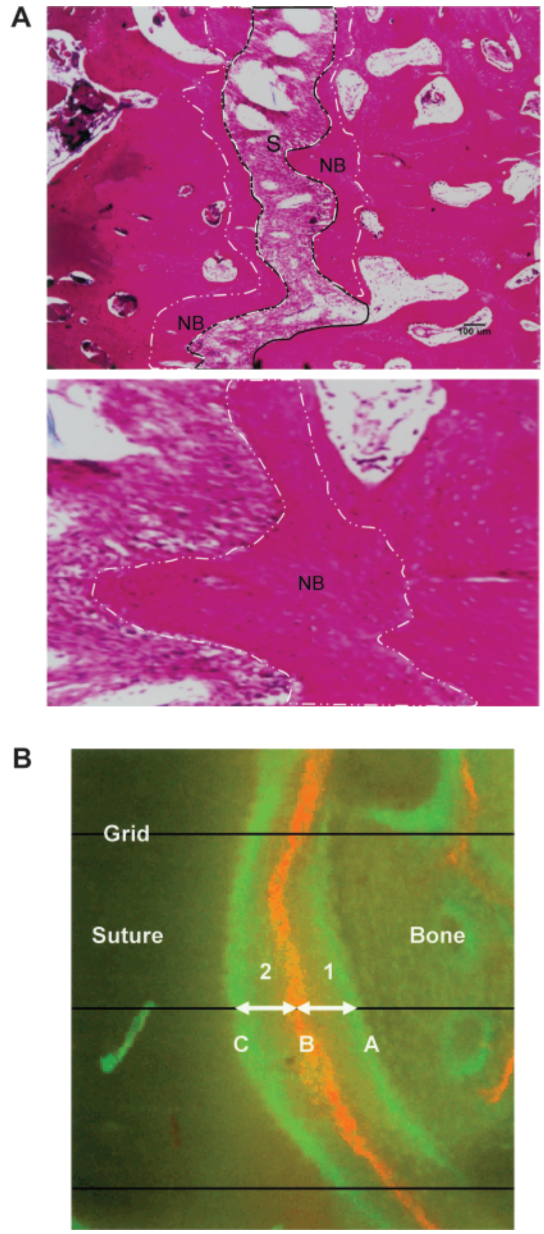

Figure 4 (**A**) Top: area measurements of the suture (S) and new bone (NB); bottom: closer view showing fibre orientation and (**B**) 1: inter-label width AB. 2: inter-label width CD. A: oxytetracycline (day 7), B: calcein (day 17), and C: oxytetracycline (day 27). Bar = 100 µm.

Bristol, UK) with a 95 per cent confidence interval ($P < 0.05$). The fixed part of the models was used to compare the groups and time intervals. Because MAR and BFR were acquired as repeated measurements over two time intervals (days 7–17 and days 17–27), a two level model was used, with animals at one level, and time intervals at the second level. The measurements of new bone formation, suture area, and overall sutural expansion were evaluated at one time point (end-of-experiment) and required only a one level model.

The curves describing the changes of the repeated calliper, radiographic widths, and weight measurements were modelled over time as polynomials. The fixed part of the models described the changes that occurred as a function of time and statistically compared groups. Iterative generalized least squares were used to estimate the polynomials.

Results

The animals increased their weights by approximately 3–9 per cent and showed no obvious signs of discomfort during the study. One rabbit in the intermittent group lost two MSIs between days 1 and 2; it was reclassified to the control group. A continuous group rabbit lost two MSIs on day 18; it provided biometric data up to day 17, but was not included in the histomorphometric analyses. The overall MSI success rate was 86 per cent (24 out of 28).

Biometric

The biometric measurements showed significant group differences in sutural separation over time (Table 1). The continuous group, which demonstrated the greatest separation, displayed a curvilinear—decelerating—pattern of expansion

Table 1 Fixed and random parts of the polynomial models describing longitudinal width changes in the control and experimental groups (constant fixed at day 29).

Width	Group	Fixed part						Random part			
		Constant		Day		Day^2		Between animals		Between days	
		Coefficient	SE	Coefficient	SE	Coefficient	SE	Variance	SE	Variance	SE
Bone marker	Continuous	10.300	0.700	0.009	0.014	−0.001	0.000	3.377	1.810	0.061	0.013
	Intermittent	8.985	0.507	0.027	0.002			1.536	0.888	0.010	0.002
	Control	7.981	0.646					2.071	1.310	0.000	0.000
Miniscrew implant radiograph	Continuous	12.910	0.660	0.008	0.028	−0.003	0.001	2.821	1.529	0.224	0.055
	Intermittent	11.900	0.473	0.035	0.003			1.329	0.768	0.025	0.007
Miniscrew implant top	Continuous	12.910	0.070	0.007	0.032	−0.002	0.001	2.840	1.545	0.294	0.072
	Intermittent	11.580	0.479	0.025	0.004			1.345	0.782	0.061	0.016
Miniscrew implant bottom	Continuous	12.690	0.676	0.001	0.032	−0.002	0.001	2.898	1.577	0.297	0.073
	Intermittent	11.500	0.476	0.022	0.008			1.236	0.736	0.233	0.060

SE, standard error; width = constant + (coefficient × day) + (coefficient × day^2).

for both the radiographic and calliper measurements; the intermittent group showed a linear pattern of increase (Figures 5 and 6). Inter-bone marker widths increased 1.28 mm in the continuous force group and 0.78 mm in the intermittent force group. The control group showed no significant changes in inter-bone marker widths (Figure 5A). Inter-MSI widths measured radiographically increased 2.35 mm and 0.78 mm between day 0 and 29 in the continuous and intermittent groups, respectively (Figure 5B).

Calliper width measurements taken at the tops of the MSIs increased 2.30 mm in the continuous group and 0.73 mm in the intermittent group (Figure 6A). For width measurements taken at the bottoms of the MSIs, there was an increase of 2.06 mm in the continuous group and of 0.64 mm in the intermittent force group (Figure 6B).

Histomorphometric

HE sections showed stretched collagen fibres in the midsagittal suture, osteoblasts at the sutural margins, new bone formation and Sharpey's fibres connecting the bone and suture in both the continuous and intermittent force groups (Figure 7). In the control group, the midsagittal suture remained intact and showed minimal or no new bone formation.

New bone formation, sutural, and overall expansion areas were all greater in the continuous than the intermittent group, followed by the control group (Figure 8). While the continuous group consistently showed larger area measurements than the intermittent group, none of the differences were statistically significant (Figure 9A). All area measurements in the control group were significantly less than in the two experimental groups. The ratio of new bone formation to overall sutural expansion was significantly less in the control group than in the continuous and intermittent groups. The ratio showed no significant difference between the continuous and intermittent force groups (Figure 9B).

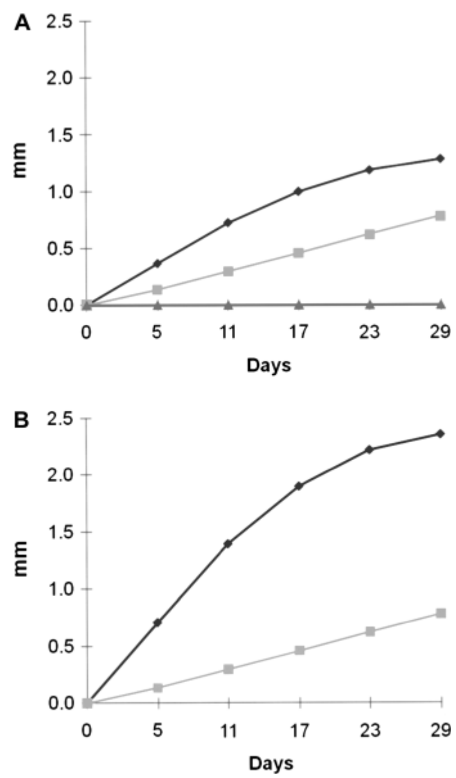

Figure 5 Longitudinal radiographic changes (mm). (**A**) Inter-bone marker widths and (**B**) inter-miniscrew implant widths for the continuous force ♦, the intermittent force ■, and the control ▲ groups. Initial measurements (day 0) have been adjusted to zero by subtraction.

The bone labels showed significant differences in the rates of bone formation between the three groups. In the control group, the labels were almost overlapping, indicating minimal bone growth; the experimental groups demonstrated clear separations between the three labels (Figure 10). MAR was significantly greater in the continuous than in the intermittent group, which was in turn significantly greater than in the control group, both between days 7 and 17 and between days 17 and 27 (Figure 11A). MAR between days 7 and 27 was also significantly greater in the continuous than the intermittent group, followed by the control group. MARs within each group remained constant over time; there were no significant differences in MAR between days 7 and 17 and days 17 and 27.

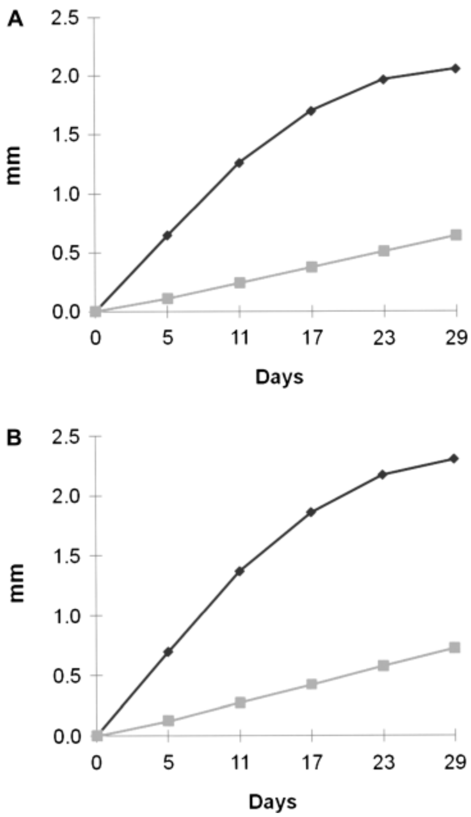

Figure 6 Longitudinal changes (mm) of calliper width measurements taken at the top (**A**) and bottom (**B**) of the miniscrew implants for the continuous ♦ and intermittent ■ force groups. Initial measurements (day 0) have been adjusted to zero by subtraction.

BFR also showed significant group differences. BFR was significantly greater in the continuous than in the intermittent group, and both were significantly greater than in the control group between days 7 and 17 and 17 and 27 (Figure 11B). As with MAR, BFR between days 7 and 17 was not significantly different than BFR between days 17 and 27 for either of the experimental groups. BFR between days 7 and 27 was significantly greater in the continuous than in the intermittent group, followed by the control group.

Discussion

Most of the 3 mm MSIs withstood the 50 g expansion force and provided stable skeletal anchorage. The MSI success rate (86 per cent) was similar to or slightly less than previously reported after immediate loading (Melsen and Costa, 2000; Carrillo *et al.*, 2007; Owens *et al.*, 2007). The first pair of MSIs was lost between days 1 and 2, probably as a result of trauma-induced changes in the bone that occurred during insertion (Schatkzer *et al.*, 1975). Failure is commonly due to the destruction of the bone threads formed around the screw (Schatkzer *et al.*, 1975; Collinge *et al.*, 2000; Ikumi and Tsutsumi, 2005). which causes the bone to strip and the screw to fail (Carano *et al.*, 2005). On day 18, the second pair of MSIs was lost. Since there were no signs of infection, this may have been due to insufficient secondary stability associated with inadequate bone healing or micromovements (Carter and Giori, 1991; Goodman *et al.*, 1993; Heller *et al.*, 1996). Since the MSIs in the present study were 3–4 mm shorter than those commonly used MSIs, the relatively high success rate supports the notion that screw diameter is more important than length for stability (Miyawaki *et al.*, 2003).

Sutural separation

The biometric and histomorphometric results showed that continuous forces produced substantially more sutural

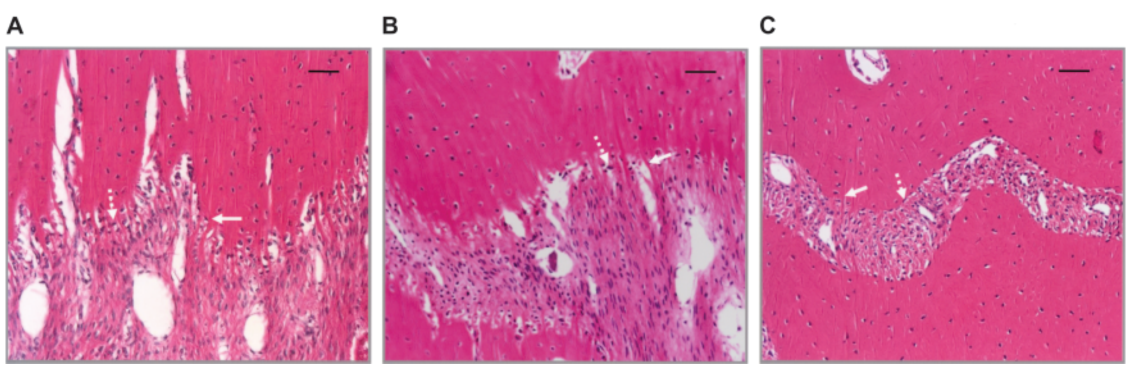

Figure 7 Sutural bone formation in (**A**) the continuous and (**B**) the intermittent groups after expansion and (**C**) the control group without expansion. Sharpey's fibres (solid arrow) were stretched and embedded in osteoid; osteoblasts (dotted arrow) deposited at the bone margin. Bar = 25 μm.

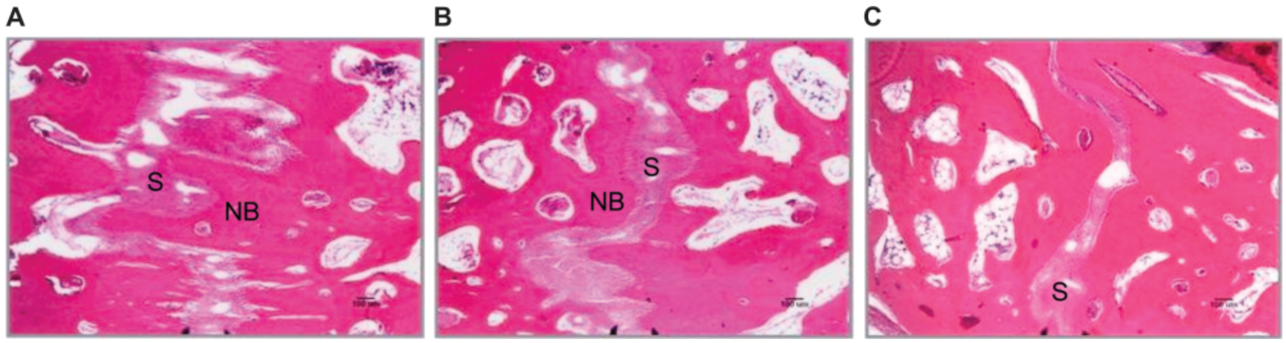

Figure 8 Haematoxylin and eosin stained coronal sections from (**A**) the continuous, (**B**) the intermittent, and (**C**) control groups. Bar = 100 μm. NB, new bone; S, suture.

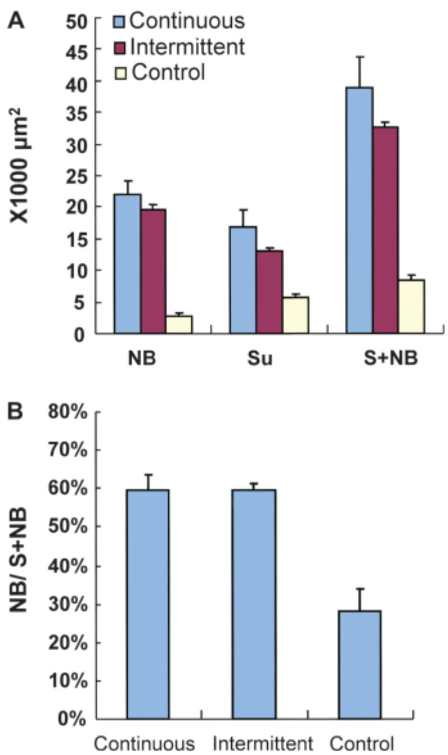

Figure 9 Group comparisons of (**A**) new bone formation area (NB), suture area (Su), and overall (S + NB) expansion area and (**B**) the ratio of new bone formation to overall expansion area (Bars = standard errors).

separation than intermittent forces. This supports findings showing that both the amount and duration of force are important for determining the amount of sutural separation (Hickory and Nanda, 1987; Mörndal, 1987; Steenvoorden *et al.*, 1990). If sutural separation is proportional to duration, then the intermittent forces that were delivered for 25 days should have produced 86 per cent as much expansion as the continuous forces delivered for 29 days. However, the intermittent forces only produced 61 per cent as much sutural separation. This indicates that there was approximately a 25 per cent sutural relapse in the intermittent group during the four, one-day breaks that the NiTi open coil springs were ligated.

The bones adjacent to sutures are connected by collagen fibres that have been shown to stretch during expansion (Murray and Cleall, 1971; Storey, 1973). Stretched collagen fibres retain pull-back potential for considerable periods of time. For example, gingival fibre bundles remain stretched for up to 33 weeks after tooth rotation (Reitan, 1959). The pull-back potential of the fibres may explain why maxillary expansion relapses without retention (Hicks, 1978). Alternatively, the difference may be due to changes in the growth dynamics of the tissues associated with the intermittent forces. Regardless, the sutures separated with intermittent forces did not totally rebound to their original width, even though they were not retained. The amount of relapse may have been limited by new sutural bone formation.

The rates of sutural separation decelerated over time with continuous forces and remained constant with intermittent forces. With continuous forces, sutural width increased almost linearly until day 11, after which the rates regularly decreased. This suggests increased resistance to expansion after day 11, perhaps due to interferences from other bones or non-compliant soft tissues. While 11-week-old White New Zealand rabbits can be considered as young adults (Masoud *et al.*, 1986), the increased resistance was probably not due to sutural interdigitation because the sutures showed the greatest rates of initial expansion. Another explanation for the decelerated sutural separation rates might be simply because binding occurred between the guide wire and the holes of the implant heads. Since the pattern of expansion was linear, the intermittent group may not have attained the critical amount of sutural separation necessary for developing resistance. Alternatively, the linear pattern may represent the adaptation of the suture following partial relapse during the four breaks. This suggests that lower magnitudes of continuous force may produce more physiological sutural separation with less relapse potential.

In contrast to the intermittent forces, continuous forces demonstrated considerably greater increases in inter-MSI than inter-bone marker widths. With continuous force, MSIs and bone markers increased 1.3 and 0.7 mm, respectively, before the rates started to decelerate. Despite the lack of significant differences, calliper width measurements taken

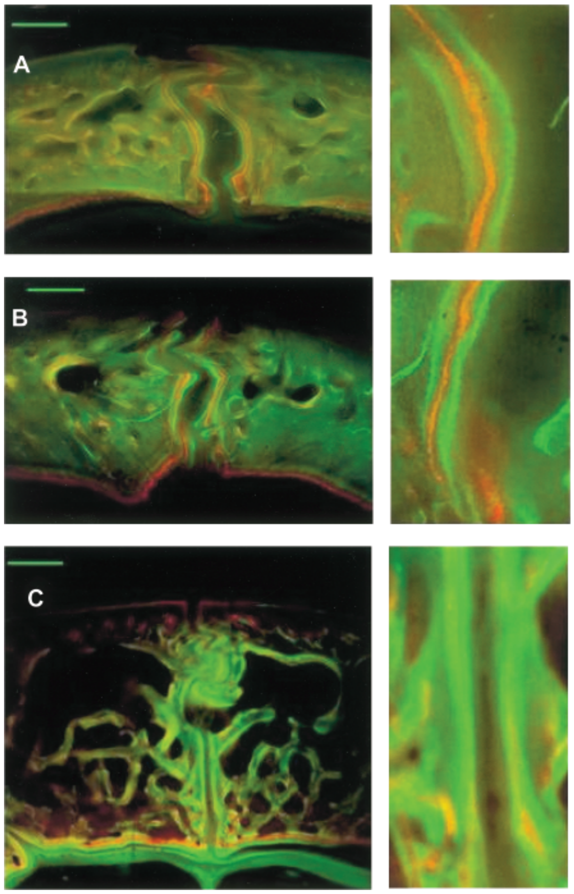

Figure 10 Fluorescent labelled sections. The oxytetracycline (green) label close to the bone marrow was given at day 7, the calcein (orange) label was given at day 17, and the oxytetracycline (green) label, adjacent to the midsagittal suture, was given at day 27. (**A**) The continuous force group. (**B**) The intermittent force group. (**C**) The control group. Notice that distances between green and orange lines were greater in the continuous than in the intermittent and control groups under higher magnification. Bar =1 mm.

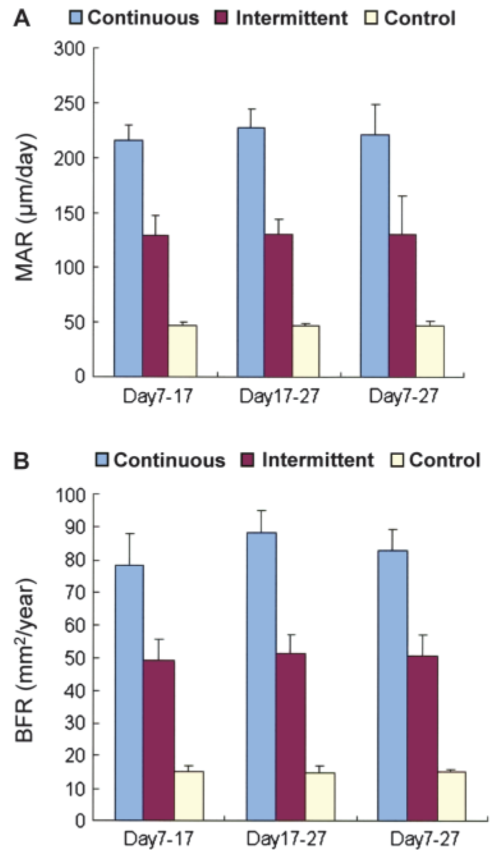

Figure 11 Comparisons of (**A**) mineral apposition rate and (**B**) bone formation rate for the controls and experimental groups (Bars = standard errors).

at the tops of the MSIs were consistently greater than comparable measurements taken at the bottom. Tipping of the MSIs, indicating triangular expansion of bone, might be expected because the forces were exerted above the suture. Triangular expansion, with a centre of rotation located approximately at the nasal bridge, has been demonstrated for the midpalatal suture (Wertz, 1970). The MSIs showed only limited amounts of tipping, perhaps due to the fact that the force vectors were located close to the bone or due to the relatively rigid 0.020 inch wire supporting the coil springs. Movements of the MSIs within the bone could also explain the small differences observed; it has been previously shown that MSIs can move up to 2 mm within bone during orthodontic treatment (Liou *et al.*, 2004; Mortensen, 2007).

Bone formation

MAR and BFR were higher with continuous than intermittent forces. As a percentage of continuous force, the mineralization and BFRs with the intermittent forces were 59 and 61 per cent, respectively. Intermittent forces also increased inter-bone marker widths approximately 61 per cent as much as continuous forces. Moreover, independent of the type of expansion, sutural bone formation was proportional to sutural separation. As a percentage of the overall expansion area, bone formation was approximately 60 per cent for both the continuous and intermittent forces. This suggests that there is a relationship between the amounts of sutural separation and bone formation. During expansion, the periosteum that surrounds the bony margins is stretched by the collagen fibres connecting the two sides, which initiates sutural bone formation (Murray and Cleall, 1971). Greater amounts of expansion might therefore be expected to produce greater stretch of the periosteum and greater bone formation (Parr *et al.*, 1997). These relationships remain to be established experimentally.

While oscillating loads favour long bone adaptation (Robling *et al.*, 2001b), the intermittent forces produced smaller MAR and BFR than the continuous forces. It has been established that dynamic (oscillating) loading can trigger greater endocortical and periosteal bone formation than static (constant) loading (Hert *et al.*, 1971; Lanyon and Rubin, 1984). With prolonged loadings, bone fails to 'sense' further stimulations and reduces bone formation (Rubin and Lanyon, 1984; Umemura *et al.*, 1997). Bone formation activities have been increased by inserting breaks or recovery periods between loadings (Robling *et al.*, 2001a; Srinivasan *et al.*, 2002; Saxon *et al.*, 2005). However, the intermittent forces with four one-day breaks produced less bone formation, suggesting that sutural and long bone formation adapt differently to mechanical stimulations.

Regardless of the type of force delivered, BFRs remained constant over time. In other words, MARs and BFRs showed no significant differences in the changes that occurred between days 7 and 17 or between days 17 and 27. Temporal changes in BFRs of expanded sutures have not previously been evaluated. Using a rat leg four-point bending model, it has been shown that BFRs are significantly greater after 6 weeks than 12 weeks, while rates after 12 weeks are in turn greater than BFRs after 18 weeks (Cullen *et al.*, 2000). This again indicates that there may be different mechanisms controlling long bone and sutural bone formation. Long bone formation is controlled by sensitivities of osteocytes (Skerry, 2008), while sutural bone formation appears to be controlled by fibre stretching (Storey, 1973; Ten Cate *et al.*, 1977).

The experimental model used in the present research provides a novel approach for evaluating the quantitative relationships between forces, separation, and bone formation across sutures. While sutures have been previously expanded with varying forces, experimental outcomes remain unclear due to the lack of control over the forces (Hinrichsen and Storey, 1968; Hickory and Nanda, 1987; Southard and Forbes, 1988). Using osseointegrated implants as anchorage, Parr *et al.* (1997) showed no differences in bone formation between 1 and 3 N of expansion forces. While their model was similar to that used in the present study, osseointegrated implants are more limited than MSIs in terms of potential implants sites; they also require more invasive techniques and produce more tissue damage.

Because it is morphologically similar to the rabbit midsagittal suture, the human midpalatal suture could be expanded using MSIs and NiTi springs (Persson *et al.*, 1978). It has been shown that 350 g of continuous force anchored to the teeth can open the midpalatal suture of adolescents (Karaman, 2002). On this basis, 300–400 g of force or less when anchored to bone should be sufficient to expand the midpalatal suture in growing individuals.

Conclusion

Within the limits of this study, continuous forces produced greater sutural separation, mineral apposition, and BFRs than the intermittent forces. On this basis, continuous forces are more effective for expanding sutures than intermittent forces.

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