European Journal of Orthodontics 24 (2002) 159–166

The effect of continuous intrusive force on human pulpal blood flow

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SUMMARY The purpose of this study was to examine the effect of continuous intrusive force application on human pulpal blood flow (PBF). Recordings were made of 13 vital upper left central incisors in 13 healthy participants (experimental group, $n = 8$; control group, $n = 5$) who had clinically healthy tooth crowns and periodontal tissues. PBF was recorded by means of a laser Doppler flow meter (LDF) with an opaque rubber dam applied to the teeth. The basal blood flow in the pulp (BBFP) was compared during three observation periods: (1) before orthodontic archwire engagement; (2) during wire engagement (control group: no application of force; experimental group: continuous intrusive force of 0.5 N); and (3) after the removal of the wire. In the experimental group, brief intrusive forces (magnitude 0.5, 1.0, and 2.0 N) were applied to the incisal edge of the examined teeth to determine their effect on acute changes in PBF.

The results obtained were as follows: (1) the BBFP in the experimental group was significantly reduced during the period of continuous intrusive force application ($P < 0.05$), which was followed by recovery after the removal of the wire. (2) Brief intrusive force produced a significant reduction of PBF ($P < 0.05$), but the reduction rate (percentage) did not differ significantly during the observation periods. The results indicate that the measurement technique shown in this study could detect PBF change produced by continuous orthodontic force application.

Introduction

Orthodontic force application is considered to cause pulpal tissue change due in part to the compression of the blood vessels supplying the pulp in the bony socket. In early studies, monitoring of pulpal blood flow (PBF) change was made by the following measurement techniques: histological observation (Anstendig and Kronman, 1972), pulp tissue respiration rate (Hamersky *et al*., 1980; Unsterseher *et al*., 1987), direct microscopic observation (Guevara and McClugage, 1980), and fluorescent microsphere injection (Kvinnsland *et al*., 1989; Vandevska-Radunovic *et al*., 1994). These measurement methods have technical limitations that allow observation only once in each tooth examined.

Laser Doppler flowmetry (LDF; Holloway and Watkins, 1977) can measure repeatedly PBF of the same tooth without causing any damage to the pulp (Gazelius *et al*., 1986, 1988; Olgart *et al*., 1988). The laser light incident on the tooth surface in part reaches tooth pulp via enamel prisms and dentinal tubules, and therefore the reflected Doppler-shifted signal is likely to be from the pulp (Odor *et al*., 1999). The validity of this technique has been confirmed using extracted teeth in which artificial blood circulation was examined (Vongsavan and Matthews, 1993a).

LDF does not estimate absolute blood flow value; however, it is able to monitor relative change during continuous measurement. LDF has been used for monitoring transient PBF changes produced by brief intrusive force application (Barwick and Ramsay, 1996; Brodin *et al*., 1996). To date it has not been elucidated whether such transient responses of PBF could change under continuous orthodontic force application. Furthermore, available information is limited on the effect of continuous orthodontic force application on the basal blood flow in the pulp (BBFP). According to a report by McDonald and Pitt Ford (1994), light tipping force produced a transient reduction of PBF followed by an increase. However, due to the difficulty of accurate repositioning of the LDF probe throughout the experimental period, the period of the force application (and measurement) in that study was 72 hours. The change in BBFP by continuous orthodontic force application over a longer measurement period, such as the interval of the adjustment of orthodontic force application in clinics (3–4 weeks), has been uncertain.

Care must be taken in PBF measurement to eliminate signals of periodontal blood flow origin, as the laser light incident on the tooth surface scatters to a wide area outside the tooth (Ikawa *et al*., 1999). The effect of application of an opaque black rubber dam on the elimination of such signals has been reported (Matthews *et al*., 1994, 1996; Hartmann *et al*., 1996). There are no previous reports on the effect of orthodontic force application on PBF using LDF or a detailed description with regard to the elimination of signal contamination.

Therefore, the purposes of the present study were: (1) to establish a measurement technique that allowed repeated measurement of PBF in humans over longer experimental periods with dam application in order to eliminate signals due to periodontal blood flow; and (2) to examine the effect of continuous intrusive force application on PBF.

Subjects and methods

Subjects

Recordings were made in 13 staff members of Tohoku University School of Dentistry Hospital, aged 27–31 years (nine men and four women, five control and eight experimental), who had healthy upper left central incisors and periodontal tissue. The teeth were considered as healthy if they were free of caries, restoration, defects, attrition, and discolouration, and the gingiva if it had a normal appearance, the depth of the gingival sulcus was less than 2 mm, and there was no symptomatic mobility. The purpose and the procedure were explained to the participants and their informed consent for the experiment was obtained. This study was approved by the Ethical Committees at Tohoku University School of Dentistry.

Prior to the measurements, a small acrylic disc (diameter 3.0 mm, thickness 1.5 mm) with a hole 2.0 mm in diameter was bonded to the labial surface of each examined tooth with its centre approximately 2 mm from the gingival margin using 4-META/MMA (Orthomite Super-Bond, Sun Medical Co., Japan; Figure 1). The edge of the acrylic disc was trimmed so as to avoid damage to the oral mucosa. The disc remained adhered to the tooth until completion of the scheduled recording period, ensuring guidance of the LDF probe to exactly the same position. The hole in the disc was sealed with a temporary filling (Temporary Stopping, Shofu, Kyoto, Japan) except during the recording sessions.

Laser Doppler flow meter

A blood flow monitor (type MBF3D, Moor Instruments, Axminster, UK) was used with a dental probe (external diameter 1.0 mm, fibre diameter 0.1 mm, centres 0.25 mm apart). The LDF was set up as described by Vongsavan and Matthews (1993a), with a 0.1 second time constant and an upper band-pass limit of

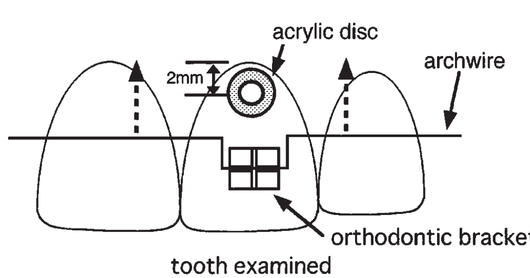

Figure 1 Schematic drawing of the continuous intrusive force application to the upper left central incisor.

14.9 kHz. The LDF signal was also recorded from a stationary reflector with the same level of illumination as present during recording from the tooth. This was used to determine the output equivalent to zero blood flow in the recording from the tooth (Vongsavan and Matthews, 1993b). The sensitivity of the blood flow monitor was adjusted using a standard suspension of polystyrene beads (Vongsavan and Matthews, 1993b) and measurements were made in arbitrary perfusion units (PU).

The analogue output from the LDF was converted to digital signals via a laboratory interface and signal processing software (Chart MacLab® System, ADInstruments Pty Ltd, Castle Hill, NSW, Australia) and stored on a computer (Macintosh Performa 5210, Apple Computer Inc.), which allowed on-line monitoring and off-line analysis of the PBF signals.

Continuous intrusive force application

Orthodontic brackets (0.022 × 0.028 inch; Supermesh Standard, Tommy International Corp. Ltd, Tokyo, Japan) were fixed to the labial surfaces of the examined teeth and upper first molars using 4-META/MMA resin (Orthomite Super-Bond; Figure 1). A modified utility archwire (0.016 × 0.022 inch; Elgiloy®, Rocky Mountain Morita Co., Tokyo, Japan) was fabricated on each subject's plaster model. The archwire in the control group was prepared so as not to activate the tooth examined during the observation period. The utility arch in the experimental group was adjusted so that the experimental tooth received an intrusive force of approximately 0.5 N. The utility archwires in both groups were afterwards ligated to the brackets using ligature wires for 6 days. The buccal bridge of each wire was covered with an elastic tube (Bump-R-Sleeve®, TP Orthodontics Inc., USA) to minimize discomfort. The observation periods and the frequency of the recordings were as follows:

1. before archwire engagement (reading taken four times during the 2 weeks before wire engagement; interval 1–5 days);
2. wire engagement (6 days: reading taken at days 1, 2, 3, and 6);
3. post-engagement (5 days: reading at days 1, 3, and 5).

Brief intrusive force application

At each recording session, PBF in the experimental group was also recorded with the archwire being temporarily removed from the teeth. The tooth then received a brief intrusive force of three different magnitudes (approximately 0.5, 1, and 2 N; duration and interval: 20 and 30 seconds), which were manually applied to the incisal edge of the tooth towards its long axis using a gram gauge (Light force, Ortho Organizers Inc., California, USA). The time interval between the three forces was kept constant, as tooth intrusion is affected by the interval between forces (Picton, 1963). The PBF change (reduction rate) was expressed by the following equation:

$$(A - B)/A \times 100\ (\%)$$

where A = PBF flux immediately before the brief intrusive force application; and B = PBF flux during the brief intrusive force application. At the end of the measurement, the archwire was returned to exactly the same location and ligated in the same position as previously. During this procedure, care was taken to avoid reactivating the archwire.

Recording procedures

For the recording procedure each subject was placed in a supine position and the lips were retracted. An opaque black rubber dam was applied to the tooth, which allowed PBF measurement with the utility archwire in the mouth. An individual resin plate that had been prepared in advance on each subject's plaster model was cemented (Dycal, The L. D. Calk Division, Dentsply International Inc., Milford, USA) to the palatal surface of the tooth crown. This was carried out to ensure the appropriate application of the rubber sheet throughout all recording sessions in each subject (Figure 2). Three holes were punched in an opaque rubber sheet (Latex

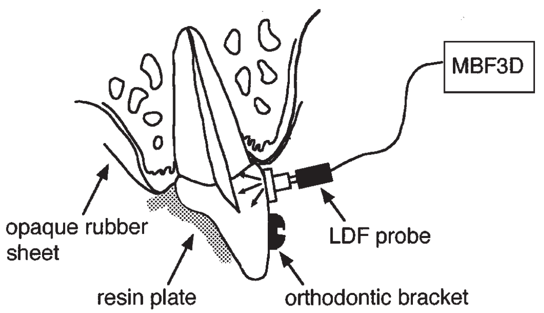

Figure 2 Schematic drawing of pulpal blood flow measurement by means of laser Doppler flowmetry in the upper left central incisor.

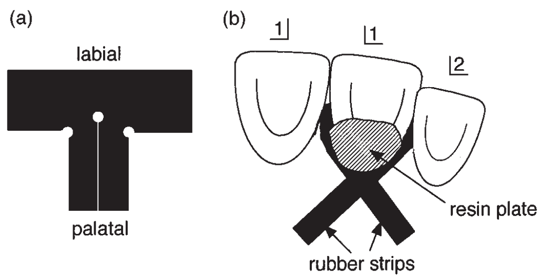

Figure 3 Schematic drawing of the preparation of the opaque rubber sheet (left) and its application to the upper left central incisor (right).

Rubber Sheeting, Four D Rubber Co. Ltd, UK; thickness: 0.25 mm), and two strips were made using scissors (Figure 3a); one strip passed through the mesial inter-proximal space of the tooth from the labial to the lingual, and the other through the distal space. Both strips were then crossed and glued to each other at the lingual side using an adhesive material (Alon alpha, Toa Gosei, Co. Ltd, Tokyo, Japan; Figure 3b).

After dam preparation, the temporary stopping was removed from the acrylic disc on the labial surface of the tooth, and a stainless steel tube (outer diameter 2.0 mm, inner diameter 1.6 mm, length 3 mm) was fitted into the acrylic disc. The tip of the LDF probe was inserted into a polythene tube (outer diameter 1.5 mm, inner diameter 1.0 mm, length 3 mm) to obtain a satisfactory fit into the stainless steel tube. PBF was then measured with the utility archwire in the mouth. During measurement, care was taken to avoid contact with any portion of the subjects by the measurement probe in order not to produce any signal artefact due to movement. The dam was then dissected using scissors and the PBF flux without the dam was measured. For the brief intrusive force application, the utility arch was temporarily removed from the teeth and the dam was re-applied. After PBF measurement with application of a brief intrusive force, the utility arch was repositioned on the tooth. The preparation and the actual recording took approximately 40 minutes. The steel tube and the resin tip on the lingual surface were removed at the end of each recording.

Data analyses

The BBFP at each recording was expressed as a percentage of the average of the four measurements before archwire engagement in each subject. The changes of BBFP in each experimental group during the observation periods were compared using a one factor repeated measurement ANOVA. The summary measures method was used to compare BBFP in the control and experimental groups, and 'area under the curve' in both groups was estimated (Matthews *et al.*, 1990). The effect of the increase in magnitude of the brief intrusive force on the reduction rate of PBF flux in each experimental period and the changes in the reduction rate during the three experimental periods were compared using one factor repeated measurement ANOVA. The effects of the dam on PBF flux were examined using the Wilcoxon signed-rank test. $P < 0.05$ was taken as indicating a significant difference.

Results

The total measurement period was between 15 and 25 (average 16.3) days. After the orthodontic archwire was activated, all the participants in the experimental group experienced a slight biting pain, which was most severe on the second day of force application. The sensation returned to a normal level by at most 5 days after removal of

Table 1 Changes in PBF flux (%) during the observation periods.

Recording session		1	2	3	4	5	6	7	8	9	10	11
Control	Mean	112.28	104.07	93.24	90.81	87.28	94.64	90.38	90.89	93.41	88.38	83.78
(n = 5)	(SD)	9.70	12.36	6.97	5.56	13.47	23.75	12.23	10.60	20.77	23.72	10.78
Experimental	Mean	104.08	102.34	98.39	95.19	74.68	70.98	68.08	67.29	103.35	107.11	103.56
(n = 8)	(SD)	12.37	16.73	11.52	9.84	19.09	16.23	20.58	23.37	17.69	15.10	21.31

Recording sessions 1–4: before wire application; 5–8: during wire application; 9–11: after removal of the wire.

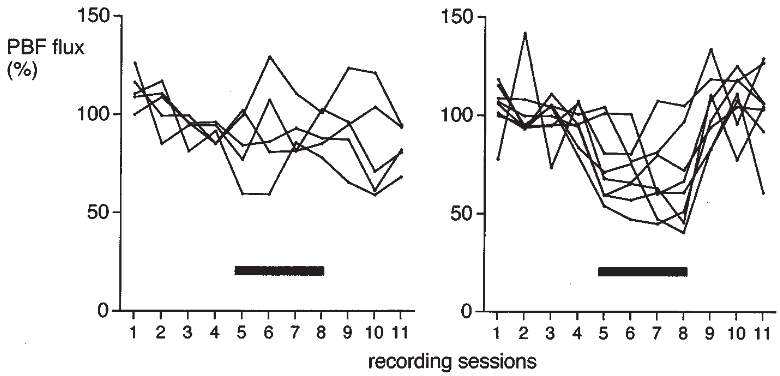

Figure 4 Changes of PBF flux in each subject during the observation periods (left: control group, right: experimental group). The ordinate and abscissa represent the PBF flux (%) and the recording sessions, respectively. Recording sessions 1–4, 5–8, and 9–11 indicate readings taken four times before wire engagement, at days 1, 2, 3, 6 during wire engagement and at days 1, 3, 5 post-engagement, respectively. Bars indicate the term of the wire engagement.

the archwire. None of the subjects complained of intrusion or discolouration of the tooth during or after the experimental periods.

There was no significant change in BBFP during the observation periods in the control group (one way repeated measurement ANOVA, P = 0.12), but there was a significant change in BBFP in the experimental group (one way repeated measurement ANOVA, $P < 0.05$; Table 1). Figure 4 shows the relative percentage changes of BBFP in each subject. 'Area under the curve' in the experimental group was significantly lower (69.63 ± 15.61%; mean ± SD) than that in the control group (90.79 ± 12.50) during the period of wire engagement (Mann–Whitney test, $P < 0.05$). During the post-engagement period, no significant difference was found (control group; 88.79 ± 16.21%, experimental group; 104.67 ± 12.75%, Mann–Whitney test, P = 0.057).

The brief intrusive force produced a transient decrease in PBF (Figure 5, Table 2). There was a significant increase in the percentage reduction rate with the increase of the force ($P < 0.05$), and a significant difference in the reduction rate between that produced by 0.5 and 2.0 N (Scheffé's test). No pattern was observed with each brief force range either before, during, or after the continuous force periods. Reduction in the rate of PBF for each force magnitude did not significantly change between the observation periods (0.5 N, P = 0.90; 1.0 N, P = 0.50; 2.0 N, P = 0.57).

The rubber dam produced a significant decrease of PBF flux (n = 84, 77.9 ± 10.2%, mean ± SD). The recorded flow value obtained without

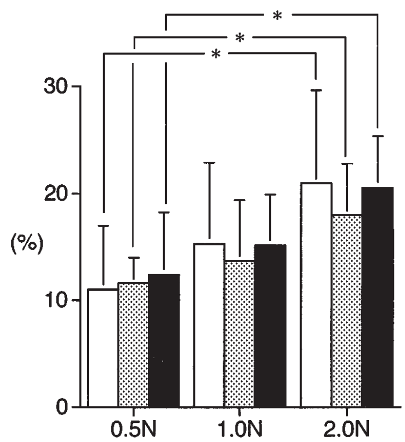

Figure 5 Reduction of PBF flux produced by brief intrusive force application in each experimental period (empty bar: before wire engagement; dotted bar: during force application; filled bar: after removal of the wire). Bars represent the mean ± SD of the PBF reduction rate (%) for each magnitude of the force (0.5, 1.0, 2.0 N). Significant differences are indicated by an asterisk (Scheffé's test).

Table 2 Mean (±SD) in the percentage reduction rate of PBF flux during brief intrusive force application in the eight experimental teeth.

Force (N)	Before wire engagement	During intrusive force application	After removal of the wire
0.5	11.04 (5.94)	11.59 (2.41)	12.40 (5.85)
1.0	15.28 (7.62)	13.70 (5.67)	15.13 (4.78)
2.0	20.96 (8.68)	17.97 (4.81)	20.53 (4.83)

the rubber dam (6.38 ± 1.92 PU, mean ± SD) was higher than that recorded with the rubber dam (1.34 ± 0.58 PU, mean ± SD; $P < 0.05$, Wilcoxon signed-rank test).

Discussion

Repeated measurement of PBF with opaque rubber dam application

The longest reported period of force application for repeated measurement of PBF in humans is 72 hours (McDonald and Pitt Ford, 1994). In the present study, the acrylic disc bonded to the labial surface of the examined tooth throughout the observation period ensured exactly the same positioning of the LDF probe and thus repeated measurement, i.e. day-to-day change of BBFP was carried out for up to 25 days including 6 days of continuous force application. The insignificant change of BBFP in the control group showed that this measurement technique did not significantly affect BBFP, and therefore may also be applicable to other treatment approaches such as rotation, extrusion, and bodily movement.

There are no reports in the literature on BBFP measurement by means of LDF during continuous orthodontic force application or any detailed description of the elimination of the signal component of periodontal blood flow origin. In this study, an opaque rubber sheet was used which included strips tied at the cervical portion of the tooth in order to eliminate signal contamination. The magnitude of the reduction found in PBF was similar to that in previous reports where a conventional rubber sheet was applied (Matthews *et al*., 1994; Hartmann *et al*., 1996). This may be explained as follows: (1) the signal component of PBF origin, which is considered to be mainly produced by scattering of the laser light to the cervical gingiva, is cut off by the opacity of the rubber sheet; (2) due to the resin veneer on the lingual and the resin disc on the labial surface, the rubber strips were sufficiently inserted into the gingival sulcus, and compressed the gingiva, which reduced the blood flow to this region.

The effect of continuous intrusive force on PBF

In the experimental group, continuous intrusive force produced a reduction of BBFP during the period of force application. Although the magnitude of the apical displacement was not measured, the intrusive force of 0.5 N was considered sufficient to produce a change in BBFP. According to Picton (1963), a brief intrusive force of 50 g causes an apical tooth displacement of approximately 40 µm, which is considered to be sufficiently large to distort blood vessels 30–150 µm in diameter (Takahashi *et al*., 1982). The reduction of BBFP during the period of force application followed by recovery indicates that the produced change in BBFP is reversible and the pulpal circulatory system can deal with an apical displacement produced by an intrusive force of 0.5 N. This supports the general concept that the recommended orthodontic force should be between 40 and 50 g (Ricketts *et al*., 1979). In the present investigation, the archwire was removed for several minutes at each recording session in order to give a brief intrusive force. Further studies may be required to examine the effect of uninterrupted continuous force on BBFP.

PBF significantly decreased with an increase in brief intrusive force, which is in agreement with the findings of Brodin *et al*. (1996). The reduction is considered to be produced by compression of the blood supplying vessels due to the transient apical displacement of the tooth. The reduction rate (percentage) for each magnitude of force, however, did not change between three measurement periods. This may be interpreted to mean that during continuous intrusive force application there was a difference between the day-to-day changes in BBFP and the PBF responses to transient tooth movement. In the present study, the results indicate that the repeated measurement of PBF at different stages of orthodontic force application may be more suitable for evaluation of pulp haemodynamics than a single measurement during orthodontic force application. This supposition is premature, but merits further investigation to examine the possibility of repeated measurement of PBF as one of the criteria of optimal orthodontic force application.

Conclusions

1. A measurement technique that allows repeated measurement of human PBF using LDF with opaque rubber dam application was established, and the effects of continuous intrusive force on human PBF were examined.
2. In teeth that received continuous (6 consecutive days) intrusive force of 0.5 N, BBFP was significantly reduced during the period of force application ($P < 0.05$).
3. Brief intrusive force (0.5–2.0 N) produced a significant reduction of PBF ($P < 0.05$), but the reduction rate did not significantly differ during the observation periods ($P > 0.50$).
4. The results suggest that the repeated measurement of PBF at different stages of orthodontic force application may be more suitable for evaluation of pulp haemodynamics than a single measurement during orthodontic force application.

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Acknowledgements

The authors wish to thank Professor Keishiro Karita for the valuable discussion. We appreciate the assistance provided by Ms Miyuki Fujiwara and Ms Elizabeth Webeck in preparing the manuscript. We are also grateful to D. Mrozek for linguistic help. This study was in part supported by a Grant-in-Aid for Scientific Research (No. 10671923) from the Ministry of Education, Science, Sports and Culture, Japan to Motohide Ikawa.

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