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Diagnostic characteristics of pulpal blood flow levels associated with adverse outcomes of luxated permanent maxillary incisors

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Abstract – Laser Doppler flowmetry (LDF) is a non-invasive method to assess pulpal blood flow (PBF). Dental injury has been associated with significant PBF reduction. The purpose of this study was (i) to describe PBF characteristics of teeth with specific clinical outcomes, and (ii) to demonstrate diagnostic characteristics for different threshold PBF values for detection of specific multiple adverse outcomes. In 80 trauma patients, a single maxillary incisor treated by repositioning and splinting, and the respective contralateral homologous control tooth were investigated by LDF to assess local PBF values. Perfusion units (PU) were taken in two sessions, on the day of splint removal (session I), and 12 weeks after splint removal (session II). The ability of session II-related PBF measurements at 2.9, 6.4 and 9.9 PU levels to identify adverse outcomes occurring 36 weeks after splint removal was investigated. Adverse outcomes were classified as type I (loss of sensitivity), type II (periapical radiolucency), type III (grey discolouration), type IV (loss of sensitivity and periapical radiolucency), and type V (loss of sensitivity, periapical radiolucency and grey discolouration of crown). Receiver–operator characteristic (ROC) curves were used to evaluate the sensitivity and specificity of PBF assessments. There was a significant increase in PBF values from session I to session II ($P = 0.0001$) for teeth without an adverse outcome, while teeth affected by a type II–V outcome showed a significant decrease in PBF values ($P < 0.05$). PBF measurements did not change over time for the contralateral incisors ($P > 0.05$). A type IV and V outcome occurred in 21 and 24% of the instances, respectively. The PBF of 2.9 PU demonstrated a sensitivity of 70% and a specificity of 93% for type V outcomes. The best likelihood ratio was found for the PBF 2.9 PU level and incisors associated with a type V outcome. The data suggest that the LDF test to be a valuable diagnostic adjunct for luxated teeth showing signs of adverse outcomes including grey discolouration or a combination of other signs. However, it may also become necessary to apply clinical decision-making methods in order to correctly evaluate the

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value of information gathered. The clinical implication is that LDF may become useful in the prediction of adverse outcomes at a much earlier time period than may be accomplished by standard sensitivity tests.

Dental injuries to the permanent incisors are a frequent finding following orofacial trauma. Traumatically displaced or avulsed permanent teeth require a splint for stabilization following repositioning or replantation (1, 2). Treatment outcome of dislocated teeth may be influenced by several factors, such as degree of dislocation, concomitant dento-alveolar injuries, stage of root formation, time period between trauma and treatment and type of dental trauma splint. The course of healing of the severed periodontal ligament and the neurovascular supply to the pulp determine the treatment outcome of the injured teeth. If the tooth becomes necrotic and infected, an external inflammatory root resorption may occur, which may result in tooth loss in a short time period (3, 4).

Pulpal blood flow (PBF) measurement using laser Doppler flowmetry (LDF) has been described as a more sensitive technique for evaluating tooth vitality compared with conventional methods such as electrical and thermal pulp testing (5, 6). Several authors reported the use of flowmetric values to demonstrate the re-establishment of vitality in traumatized teeth (5–7), or to show significant blood flow reduction in maxillary teeth in patients undergoing Le Fort I osteotomy (8–11). In instances of dental trauma LDF may be useful in the detection of transient ischaemic episodes and the identification of teeth at risk for adverse outcomes such as avascular necrosis and tissue loss. The purpose of this study was (i) to describe PBF characteristics of teeth with specific clinical outcomes, and (ii) to demonstrate diagnostic characteristics for different threshold PBF values for detection of specific multiple adverse outcomes.

Materials and methods

Subjects

The study group of 80 patients undergoing dental trauma splinting included 27 females and 53 males, with a mean age of 20.5 years (range 2–56 years). The subjects were informed about the study procedure and informed consent was received. Criteria for including a patient were (i) presence of a single permanent maxillary incisor affected by a luxation injury, (ii) absence of concomitant dento-alveolar injuries, and (iii) recency of trauma <2 h. Each of the subjects was treated with a 0.16″ × 0.50″ wire (Standard Edgewise Wire; Leibinger, Mülheim, Germany). Where a maxillary incisor was missing, the injured central maxillary incisor bore a crown, was root-filled, or had a large filling, LDF data were not collected.

Splint application

The splints were bonded to the labial aspect of all maxillary incisors. The wire was cut to the desired length and then adapted to the curvature of the maxillary incisors using pliers. The splints were secured with identical light-curing composite. After placing cotton rolls in the vestibule, the maxillary incisors were dried with air. Etching of the enamel surface was performed with 37% phosphoric acid gel for 30 s (Totaletch®; Ivoclar Vivadent., Ellwangen, Germany). Subsequently, the gel was rinsed off with water from the dental unit and the etched surfaces were dried again. A thin layer of bonding agent (Heliobond®; Ivoclar Vivadent, Ellwangen, Germany) was applied using a microbrush. The bonding agent was left for 20 s prior to polymerization with a light source for another 40 s.

Apparatus

PBF measurements were performed with a laser Doppler flowmeter (Periflux PF 4001 Masters; Perimed, Järfälla, Sweden). Light with a wavelength of 632.8 nm was produced by a 1 mW He–Ne laser within the flowmeter and transmitted along a flexible fibre-optic conductor inside a specially designed round dental probe with a diameter of 2 mm (PF 416; Perimed) (8, 10–12). A fraction of the backscattered light from the tooth was returned to the flowmeter along a pair of afferent optical fibres within the probe. The optical-fibre diameter was 125 μm, and fibre-to-fibre distance was 500 μm. The flowmeter then processed the amount of Doppler-shifted light that was returned and produced an output signal. The measured voltage is linearly related to the flux of red blood cells (number of cells multiplied by their average velocity) encountered within the tooth and represents a relative measure of PBF.

The flowmeter was calibrated prior to each data collection session. The narrow band was adjusted to read zero voltage when the probe was placed against a motionless object, while a commercially available motility standard (Perimed) was used to calibrate the flowmeter on the wide band to a specific value of 250 perfusion units (PU). The artefact filter was activated, and the PBF data were collected on a wide band setting. Voltage output values were sent from the RS-232 port of the flowmeter, at a rate of 32 signals per second, to an Apple Macintosh Plus computer (Apple Computer Inc, Cupertino, CA, USA) for storage and subsequent analysis.

Table 1. Adverse outcomes associated with luxation type injuries ($n = 80$)

Diagnostic group	Diagnostic criteria
Single diagnosis	
Type I	Loss of sensitivity
Type II	Presence of periapical radiolucency
Type III	Presence of discolouration of crown
Multiple diagnosis	
Type IV	Loss of sensitivity and presence of periapical radiolucency
Type V	Loss of sensitivity, presence of periapical radiolucency and presence of discolouration of crown

Procedure

Measurements were recorded on the labial site of each experimental tooth at a location about 5 mm from the gingival margin. For each subject, PUs were taken in two sessions, on the day of splint removal (session I), and 12 weeks after splint removal (session II). The ability of session II-related PBF measurements at 2.9, 6.4 and 9.9 PU levels to identify adverse outcomes occurring 36 weeks after splint removal was investigated. In order to ensure accurate and reproducible spatial positioning of the probe at each session, custom-made clear plastic splints (Bioplast; Schen-Dental, Iserlohn, Germany) were prepared, covering the 80 maxillary teeth and providing appropriately placed holes with a diameter similar to that of the flowmeter probe. After having the patient rest in a supine position in the dental chair for approximately 10 min, blood flow data were collected for 3 min at each measurement session. The temperature of the room was constant. Attempts were made to minimize bias due to movement of the subjects or probe. Pulse rate and blood pressure were also recorded.

At the end of the follow up, the occurrence of adverse outcomes was assessed both clinically and radiographically. The clinical diagnostic procedures included sensitivity testing with carbon dioxide ice, and evaluation of crowns for the presence of changes in colour (13). The radiographic examination of the anterior region consisted of one occlusal film and three periapical exposures, where the central beam was directed between the lateral and central incisors and between the central incisors (13). The teeth were assigned a diagnostic outcome group according to the clinical findings. Adverse outcomes were classified as type I (loss of sensitivity), type II (periapical radiolucency), type III (grey discolouration), type IV (loss of sensitivity and periapical radiolucency), and type V (loss of sensitivity, periapical radiolucency and grey discolouration of crown) (Table 1).

In order to account for the temporal variability associated with repeated PBF measurements (12), a control group was included. At each session, when a luxated permanent maxillary central incisor was recorded, the respective contralateral homologous tooth was used as a control.

Data analysis

The mean PU for each recording site was calculated during each session by averaging all the individual PU collected for 180 s. Individual PU that registered as movement artefacts were excluded from this average.

Univariate analysis of variance for repeated measurements was used to test for statistically significant differences between session-related variations in PBF measurements. Statistical analysis of outcome group-related PBF measurements consisted of univariate analysis of variance. A Bonferroni correction of the alpha-level for diagnostic outcome group-related data was performed. Sensitivity, specificity, positive (PPV) and negative predictive values (NPV) for PBF threshold levels at ≤2.9, ≤6.4 and ≤9.9 PU (mean and standard deviation cut-off points) were calculated for each multiple diagnostic outcome group. The likelihood ratios for different PBF threshold levels to identify diagnostic outcome groups were calculated. The true-positive and false-positive rates were used to generate receiver–operator characteristic (ROC) curves to visualize the discriminative power of the LDF technique using both clinical and radiographical measurements as the gold standard. Statistical significance was set at $P < 0.05$. For all statistical analysis the SPSS 7.5.2G software program (SPSS Inc., Chicago, IL, USA) was used.

Results

At the 36-week follow up, 75% of the incisors demonstrated at least one diagnosis of adverse outcome, while only 25% showed no clinical or radiographical finding of an adverse outcome. The most common single diagnosis was loss of sensitivity (75%), followed by periapical radiolucency (34%)

and grey discolouration (20%). A type IV and V outcome occurred in 21 and 24%, respectively.

Analysing the data according to session-related measurements, there was a significant increase in PBF values from session I to session II ($P = 0.001$) for teeth without an adverse outcome at the 36-week follow up, and a significant decrease in PBF values from session I to session II ($P < 0.05$) for teeth affected by a type II–V outcome, while no significant difference between the postsplinting PBF values were found for teeth with a type I outcome ($P > 0.05$). PBF did not change over time for the control group ($P > 0.05$). Statistically significant differences between PBF values for the different outcome groups were demonstrated using univariate analysis of variance ($P = 0.000$). Bonferroni comparisons identified PBF values of teeth without an adverse outcome as significant higher than those of the other outcome groups ($P = 0.000$), and group I outcome PBF values as significant higher than those of outcome group III ($P = 0.043$) (Table 2).

The frequency distribution of false and true identification of type IV and V outcomes and PBF cut-off values of ≤2.9, ≤6.4 and ≤9.9 PU were used to calculate sensitivity, specificity, PPV and NPV. Thus, the use of PBF ≤9.9 PU as the diagnostic indicator for adverse type IV and V outcomes would identify 100% of incisors associated with the clinical diagnostic criteria of 'loss of sensitivity and periapical radiolucency' and 'loss of sensitivity, periapical radiolucency and grey discolouration of crown'. The specificity at this threshold value, however, is very low and the test would falsely identify a great number of incisors to be associated with type IV and V outcome. At the other end of the scale using 'loss of sensitivity, periapical radiolucency and grey discolouration of crown' to designate a type V outcome, the PBF ≤2.9 PU yielded a high specificity and a high sensitivity correctly diagnosing 93% of non-type V outcomes and 70% of type V outcomes. Sensitivity and specificity values using PBF ≤6.4 PU fell between values observed using 2.9 and 9.9 PU. The predictive power of a positive PBV test in identifying an incisor associated with an adverse outcome varied between 15 and 58%. The lowest and highest predictive values were found for a type V outcome for PBF ≤9.9 and ≤2.9 PU, respectively (Table 3).

The best likelihood ratio was found the for PBF 2.9 PU level and incisors associated with type V outcome (Table 3). The likelihood of the LDF test correctly identifying specific outcomes is illustrated by the ROC curves (Fig. 1).

Discussion

Luxation injury is a type of dental injury that involves displacement of the tooth in the alveolar

Table 2. Diagnostic group-related PBF measurements ($n = 80$)

	PBF value (PU)					
	Session I			Session II		
Diagnostic group	Mean	SD	Range	Mean	SD	Range
Absence of adverse outcome ($n = 20$)	8.5***	2.7	7.2–9.8	9.4†	2.8	8.1–10.7
Presence of adverse outcome ($n = 60$)						
Type I ($n = 60$)	5.7	2.7	5.1–6.4	5.4††	3.1	4.6–6.2
Type II ($n = 27$)	4.9****	1.7	4.3–5.6	4.1	1.8	3.4–4.8
Type III ($n = 16$)	4.1**	1.4	3.3–4.8	3.3	1.7	2.4–4.2
Type IV ($n = 17$)	5.4**	1.7	4.5–6.2	4.5	1.7	3.6–5.4
Type V ($n = 10$)	4.2*	1.4	3.2–5.2	3.5	1.9	2.2–4.8

PBF, pulpal blood flow; PU, perfusion units.
*$P = 0.039$; **$P = 0.002$; ***$P = 0.001$; ****$P = 0.000$. Significant session-related differences.
†$P = 0.000$; ††$P = 0.043$. Significant outcome group-related difference.

Table 3. Sensitivity, specificity, and predictive values of PBF threshold values in the diagnosis of type IV and V outcomes ($n = 80$)

	IV			V		
Statistics	2.9 PU	6.4 PU	9.9 PU	2.9 PU	6.4 PU	9.9 PU
Sensitivity (%)	11.8	94.1	100	70.0	90.0	100
Specificity (%)	84.1	53.9	23.8	92.9	48.6	21.4
Positive predictive value (%)	16.7	35.6	26.2	58.3	20.0	15.4
Negative predictive value (%)	77.9	97.1	93.4	95.6	97.3	93.4
Likelihood ratio	0.2	15.1	8.1	19.4	6.2	4.5
Area under ROC curve		0.713		0.833		

PBF, pulpal blood flow; PU, perfusion units; ROC, receiver–operator characteristic.

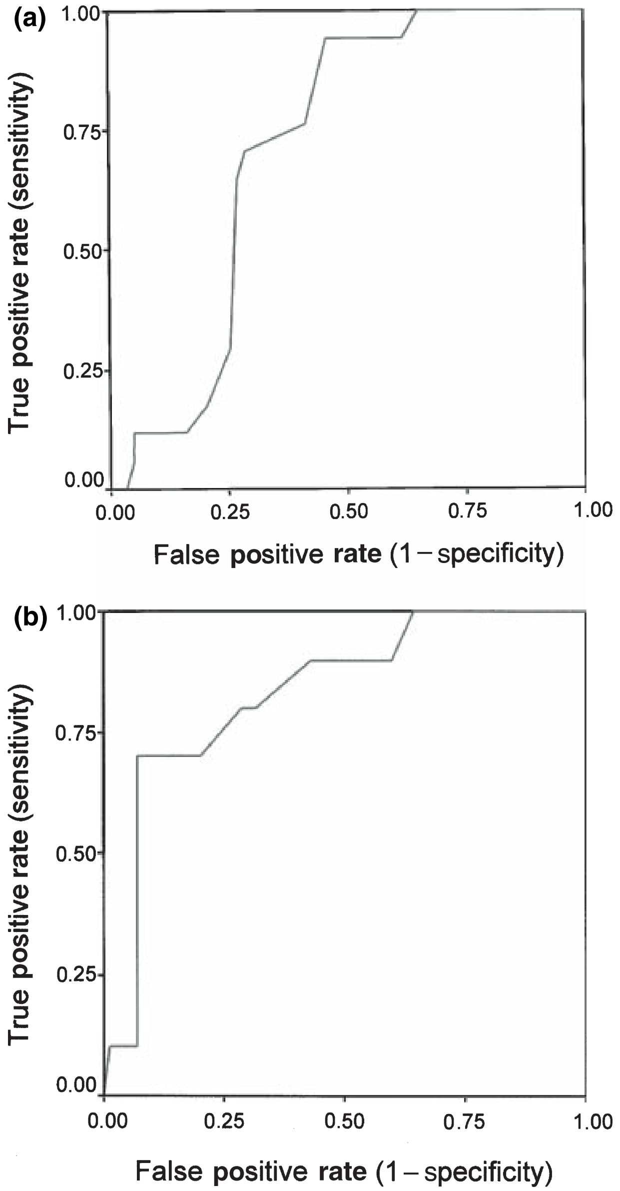

Fig. 1. Diagnostic characteristics for the full range of possible pulpal blood flow values for detection of specific multiple adverse outcomes. The area under the curve indicates the diagnostic accuracy of the test. (a) ROC curve for type IV outcome. (b) ROC curve for type V outcome. ROC, receiver-operator characteristic.

socket. It may represent a very complex wound, involving disruption of the marginal gingival seal, alveolar bone, periodontal ligament fibres, cementum and the neurovascular supply to the pulp (13). Complications include ankylosis, pulp necrosis, pulp obliteration, external root absorption and loss of marginal bone support (13–15). In several studies pulp necrosis was described as the most common complication after luxation injuries (13, 14). Prophylactic extirpation of the pulp has been recommended to prevent other complications arising from the pulp necrosis (16, 17). Treatment outcome of luxated maxillary incisors may depend on several factors such as luxation type, degree of dislocation, concomitant dento-alveolar injuries, stage of root formation, time period between trauma and treatment, and type of dental trauma splint. However, the contribution of these variables is unknown.

The present study showed that the LDF measurement was able to detect changes in PBF values after splint removal. Type II–V outcomes were associated with a significant decrease and non-adverse outcomes with a significant increase in PBF values, while type I outcomes showed no significant difference between the session-related values. At session II PBF values remained above 5 PU in non-adverse and type I outcomes, whereas in type III and V outcomes the PBF value approached and dropped below 4 PU. The significant decreases in PBF values at the 12-week follow up for type II–V outcomes is at a much earlier time period than would be expected from the standard clinical tests. This is of clinical significance and may be implicated as a possible cause in the development of subsequent degenerative and atrophic pulpal changes. Therefore, LDF may be used to monitor incisors during the post-trauma phase. It may help to identify 'ischaemic episodes' long before this may be derived from traditionally clinical tests.

A perfect test for the prediction of specific adverse outcomes should simultaneously identify teeth with and without these outcomes, thereby eliminating false-positive and false-negative scores. It is not necessary to have tests with high power of discrimination when an adverse outcome is common, therapy has few side effects although teeth without adverse outcomes are treated, and the treatment is inexpensive. However, when the adverse outcome is rare, and the side effects of therapy unfavourable, the test used must have a high predictive power to eliminate the risks for false-positive and false-negative test results.

The LDF test showed very favourable diagnostic characteristics regardless of cut-off levels for 'ischaemic disorders'. For a type V outcome, the test that was identified as having the greatest specificity and PPV also had the highest positive likelihood. The increase in the likelihood ratio as the cut-off point was lowered from the 6.4 PU level to the 2.9 PU level was due to a decrease in the false-positive rate. Choosing the 2.9 PU level as the most suitable cut-off point to distinguish teeth at risk for the occurrence of adverse type V outcomes, the sensitivity value was moderate indicating that the potential for false negatives was not low; however, the high specificity level indicates that the model would be unlikely to subject teeth to further treatment that the clinicians deemed was not necessary.

The sensitivity, specificity, PPV, NPV and likelihood ratio are descriptions of the diagnostic ability of LDF measurements at arbitrary cut-off points. The ROC curve represents a superior form of data summary as it represents the diagnostic performance of a measurement for the full range of possible cut-off points and the elimination of the bias resulting from selection of a single value. The ROC analysis reported in this study could be used by selection of cut-off points for specific adverse outcomes to optimize the identification of patients at risk of having the condition in question. The selection of cut-off points requires an analysis of the costs and benefits associated with correct and incorrect diagnosis. In the instance of adverse outcome tendency, one might want to elect a cut-off point that minimizes the number of false-negatives (teeth with adverse outcome tendency that erraneously test negative), as it is relatively simple for the clinician to take precautions to avoid adverse outcomes. The avoidance of increased treatment time and difficulty in managing adverse outcomes is a substantial benefit when compared with the minimal cost of unnecessarily taking these same precautions in a teeth with no adverse outcome tendency who is wrongly identified as having the tendency (a false-positive).

Conclusion

LDF measurements may be used as a diagnostic adjunct at luxated teeth showing signs of adverse outcomes including grey discolouration or a combination of other signs. Such knowledge would than be used to verify a clinical opinion, and to initiate endodontic treatment. However, it also become necessary to apply clinical decision-making methods in order to correctly evaluate the value of information gathered.

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