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Original Article

Efficacy assessment of laser Doppler imager in diagnosing the pulp vitality after dental trauma

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KEYWORDS
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Abstract *Background/purpose:* This is the first paper evaluating the efficacy of laser Doppler imager in diagnosis of pulpal vitality. The purpose of this study was to evaluate and compare the diagnostic benefits of laser Doppler imaging and electric pulp test (EPT) in dental trauma.
Materials and methods: Seven patients were selected for pulp vitality evaluation in Kaohsiung Medical University Hospital between 2018 and 2019. EPT and laser Doppler imager evaluation were performed for patients with traumatic injury to teeth. Statistical methods included the Kappa consistency test and the chi-square test. In addition, the receiver operating characteristic (ROC) curve, and the area under the curve (AUC) were used.
Results: There was a significant difference in Doppler flow values between the severe trauma group and the mild trauma group, regardless of patient self-reported symptoms ($P = 0.043$) or physicians' diagnostic classification ($P = 0.018$). For an EPT instrument, the Kappa coefficient was 0.67 and 1-year pulpal status findings were highly consistent ($P < 0.001$). Using a Doppler instrument, the Kappa coefficient was 0.85. According to the ROC curve, the AUC for EPT was

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0.94, the AUC for Doppler was 1, and the optimal cut-off value was 31.55, indicating that both were superior diagnostic tools.
Conclusion: Both laser Doppler imager and EPT can be used as tools for diagnosing traumatic pulp necrosis. Doppler imaging instruments allow for a more timely and accurate assessment of pulp vitality in dental trauma. In the future, ongoing research and related training are necessary for interpretation of Doppler data.

Introduction

Successful root canal treatment depends on the correct diagnosis, while endodontic testing assists in diagnosing dental pulp diseases.[1,2] Some pulp tests trigger patient feedback through the stimulation of the pulp nerve via pain pathways.[3] For example, the most widely applied electric pulp test (EPT) would rapidly produce a sharp sensation by stimulating the $A\delta$ nerve fibers in the dentin—pulp complex of the test tooth to make the patient respond to the test depending on the subjective feelings of the patients. However, it was difficult to objectively reflect the conditions of the pulp.[4]

More than 20% of people have experience of dental trauma, which was generally observed in the maxillary incisors.[5,6] When the performance of nerve growth factors was affected by the degradation of fibroblasts in the traumatic pulp, temporary paresthesia may be observed,[7] and a false negative error may be obtained in the pulp sensibility test at this time.[8,9] Nerve repair would take several months, which would only become reactive to EPT after up to 6 months, making it difficult to formulate treatment plans.[10]

To overcome the limitations of pulp sensibility tests, pulp vitality tests such as laser Doppler imaging and pulp oximetry have been developed and marketed.[11,12] Laser Doppler measurements are non-invasive, objective, painless, and semi-quantitative and have been verified to provide reliable and reproducible results in many clinical studies. A perfusion unit (PU) is used to convert the signals to red blood cell concentration and fluid velocity to assess the pulp vitality after trauma.[13] Angiogenesis was generally initiated 2 weeks to 3 months after trauma, and the indicators were expected to return to normal after the metabolites were removed by the restored blood circulation.[14]

Scholars have found that when the pulp are temporarily paralyzed due to fibroblast degradation, the traditional EPT was prone to produce false positives, while the Doppler flowmeter could detect the early changes in pulp blood flow accurately.[15] Besides, this is the first paper evaluating the efficacy of laser Doppler imager different from Doppler flowmetry in dental field. We compared the differences in the sensitivity, specificity, positive predictive value, and the accuracy between EPT and laser Doppler imager, and further explored trauma classification as well as the relationship between symptoms and pulp necrosis. We anticipate that the related examinations of dental trauma may be used as examination items to predict the risk of pulp necrosis. Laser Doppler imager may be used to provide more effective and accurate pulp vitality assessment services for trauma patients.

Materials and methods

Study design and participants

This was a prospective study with purposive sampling. From 2018 to 2019, eighteen participants with dental trauma were enrolled for evaluation of pulp vitality in the Department of Endodontics, Kaohsiung Medical University Hospital. After routine clinical examination, X-ray taking, and initial EPT checking, patients taking drugs that affected blood flow and participants with incomplete clinical records were excluded. Finally, 13 participants were included in this study. All participants were evaluated, diagnosed, and treated by the same endodontic specialist.

Based on the chief complaints and diagnosis of patients, the participants were categorized according to the trauma classification guidelines, X-ray images, and clinical examinations. The participants returned for evaluation 1 week after the trauma and were divided into two groups based on self-reported pain intensity and symptoms: mild symptom group and severe symptom group.

During the study, the pulp vitality was evaluated and recorded using the EPT and the laser Doppler imager. After 1-year follow-up period, six patients were lost of follow-up due to not returning for follow-up visits, going to clinics for root canal therapy which affected the judgment of the results tracking, and being unable to clearly express the response to EPT, and the deviation of laser Doppler settings. A total of seven participants (84 teeth) were ultimately analyzed. The correlation, consistency, test indicators, and receiver operating characteristic (ROC) curves of the pulp after 1 year were compared between the two test methods (Fig. 1).

Ethic approval and consent to participants

This experimental design was approved by the institutional review board (IRB) of Kaohsiung Medical University Chung-Ho Memorial Hospital (approval number: KMUHIRB-E(II)-20180018). Written informed consent has been obtained from the patient to publish this paper.

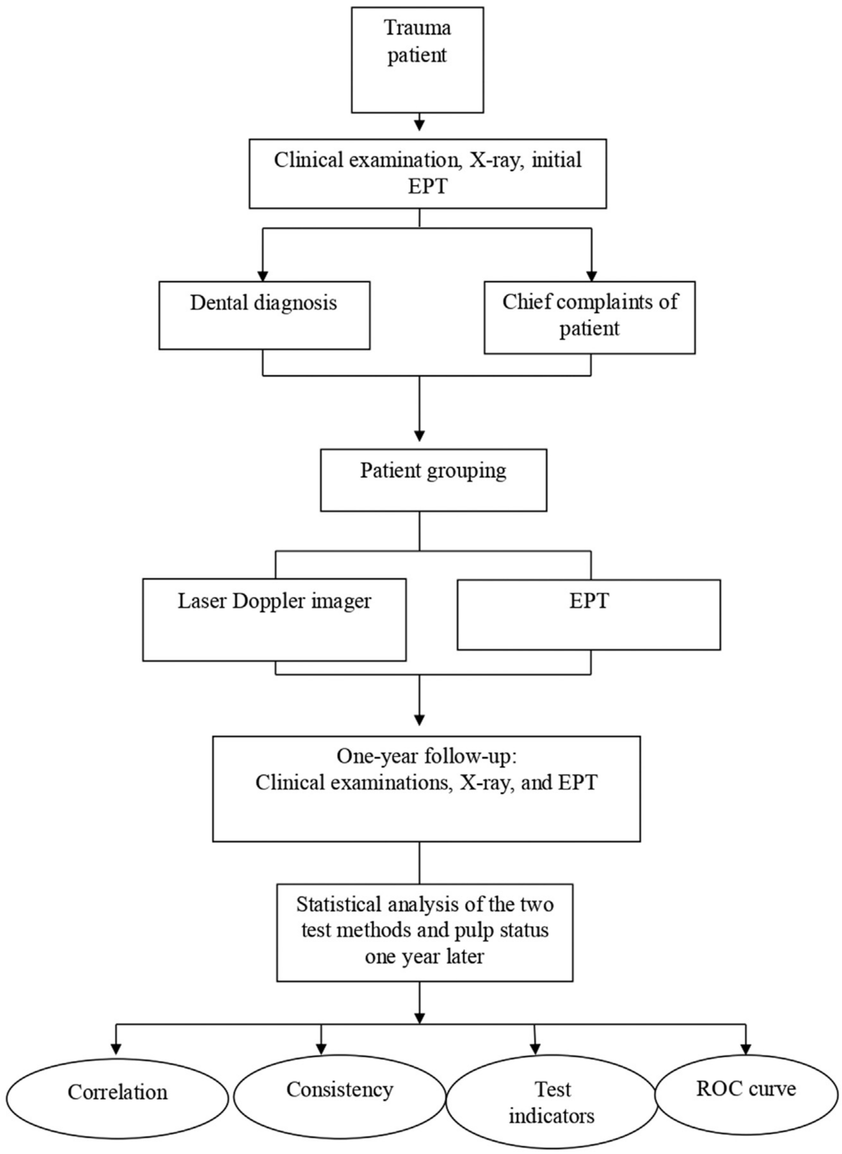


Figure 1 Schematic diagram of the study.

Pulp sensibility test records

The EPT model used in this study was Digitest D626D (Parkell Inc., Brentwood, NY, USA), which mainly rapidly elicited a sharp sensation by stimulating the Aδ nerve fibers in the pulp—dentin complex of the test tooth through microcurrent. The test tooth was dried with gauze, and toothpaste (Colgate Total, Colgate-Palmolive Company, New York, NY, USA) was applied to the probe and tooth surface as a current conductor. The procedure was repeated twice to confirm the reproducibility.

Pulp vitality test records

The laser Doppler model selected in this study was MoorLDI-2λ (Micro Star Instruments Co. Ltd., Taipei, Taiwan), with an infrared wavelength of 830 nm, a scanning frequency bandwidth of 20 Hz, and a scanning range of 6.6 cm × 5.5 cm. Flux and blood flow concentrations of microvessels within 1 mm of the skin were measured.

A single image scan is a large-scale scan of the maxillary and mandibular anterior teeth simultaneously. Normal, traumatic, and necrotic teeth were selected to perform 40 measurements per second at each point with this mode (Figs 2 and 3).

Statistical analysis

Statistical analysis was performed using the SPSS software version 20.0 (SPSS Corp., Chicago, IL, USA). The chi-square test was used to explore the correlation between patient-reported symptoms and pulp status and between physician's diagnosis as well as classification and pulp status after one year; and the sensitivity, specificity, and misdiagnosis rate of different vitality tests. The Kappa consistency test was used to determine the consistency of the

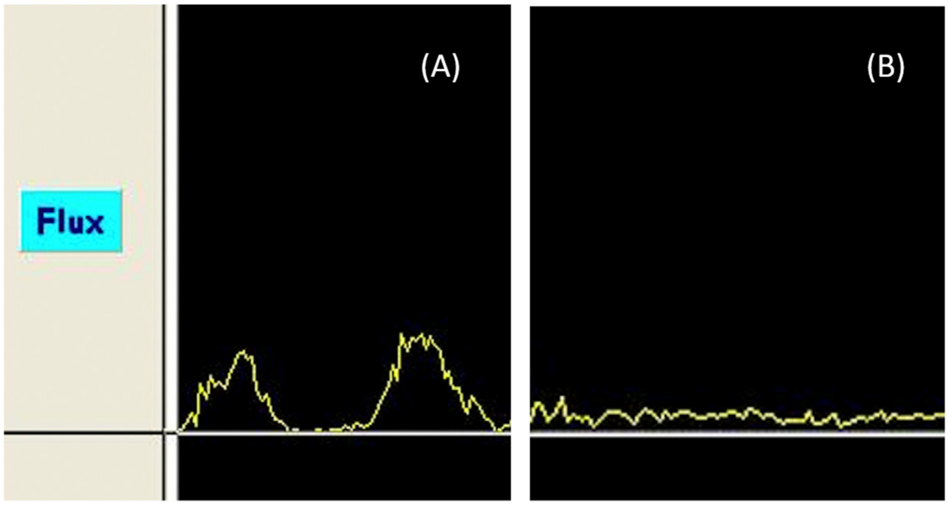
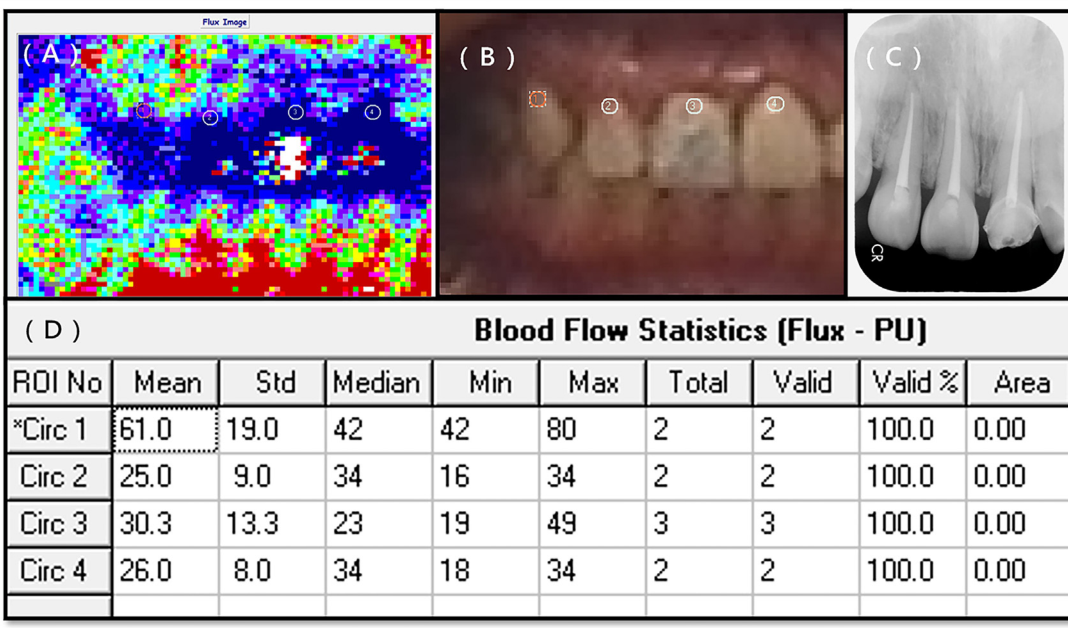


Figure 2 Waveforms of the laser Doppler imager. (A) Normal pulp. (B) Necrotic pulp.



ROI No	Mean	Std	Median	Min	Max	Total	Valid	Valid %	Area
*Circ 1	61.0	19.0	42	42	80	2	2	100.0	0.00
Circ 2	25.0	9.0	34	16	34	2	2	100.0	0.00
Circ 3	30.3	13.3	23	19	49	3	3	100.0	0.00
Circ 4	26.0	8.0	34	18	34	2	2	100.0	0.00

Figure 3 Analysis of laser Doppler images. (A) Laser Doppler image: the red area indicates areas with sufficient blood flow, while the purple area corresponds to the dental root after root canal treatment. (B) Schematic diagram of clinical positioning. (C) Corresponding radiographs: root canal treatment has been completed for the maxillary right lateral incisor, the maxillary right central incisor, and the maxillary left central incisor. (D) Data analysis of the laser Doppler imager: the data show that the perfusion volume in circle 1 is significantly higher, which is judged as a normal tooth, while the remaining three teeth are necrotic (teeth after root canal treatment), based on which the teeth are grouped. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

data of the EPT and the laser Doppler imager in the diagnosis of traumatic pulp vitality with the judgment of the pulp status after 1 year as determined by the two methods. The ROC curve was used to analyze the diagnostic area and optimal cut-points of EPT and the laser Doppler imager. The Wilcoxon signed ranks test was used to analyze the severity of trauma and patient-reported symptoms against the flux of the laser Doppler imager. The $P < 0.05$ indicated that the analysis results were statistically significant (two-tailed test). Sample size and power estimation software was G*Power version 3.1.9.4 (program written, concept and design by Franz, Universitat Kiel, Kiel, Germany). According to the research parameters and main statistical analysis method, which was the non-parametric Wilcoxon signed ranks test, when the sample size was 7, the effect size was 1.76. When the α error was set to 0.05, the statistical power was estimated to be above 0.85, and the type II error (β) was $\leq$0.15.

Results

Analysis of the flux as determined by the laser Doppler imager and the tracking of the pulp status after 1 year based on the patients' complaint and the dentists' diagnosis

The flux of the laser Doppler imager according to the chief complaints of the patients was as follows: mean ± standard deviation (SD) of the mild group was 52.17 ± 4.39, with a median and interquartile range of 53.07 (47.22–55.39). The mean ± SD of the severe symptom group was 34.28 ± 15.27, with a median and interquartile range of 29.35 (23.33–42.70).

For teeth diagnosed as mild trauma, the mean ± SD as determined by the laser Doppler imager was 53.81 ± 3.01, with a median and interquartile range of 54.79 (51.39–56.47). The mean ± SD of the flux in the severe trauma group as determined by the laser Doppler imager was 35.01 ± 11.37, with a median and interquartile range of 29.97 (26.80–42.70) (Table 1). The flux of the laser Doppler imager between the severe and mild trauma groups were compared according to patients' complaints and dentists' diagnosis, and significant differences were observed. A higher severity of the dental trauma was associated with a lower flux value of the laser Doppler imager. The classification of the severe and mild trauma groups was further analyzed using Fisher's exact test, and was found to be significantly correlated with pulp status after 1 year.

Analysis of consistency with pulp status after 1 year using EPT and laser Doppler imager

In this study, EPT instruments and laser Doppler imager were used to diagnose the condition of traumatic dental pulp and tracked the pulp status after 1 year. The Kappa coefficients were 0.67 and 0.85, respectively. The difference in the prediction of traumatic pulp vitality by EPT instruments as well as laser Doppler imager and the pulp status after 1 year was analyzed using the McNemar Chi-square test. There was no significant difference between pulp vitality as determined by the laser Doppler imager and actual pulp status after 1 year, which indicated that compared with EPT, the pulp status as predicted by the laser Doppler imager was more consistent with the actual pulp status after 1 year (Table 2).

Table 2 Kappa value and consistency analysis of electric pulp test (EPT), laser Doppler imager, and pulp status after 1 year.

		Pulp status after 1 year		Kappa[a]	McNemar tests (*P*)[b]
		Necrotic (n)	Normal (n)		
EPT	Necrotic (n)	14	10	0.67	0.002
	Normal (n)	0	60		
Doppler	Necrotic (n)	14	4	0.85	0.125
	Normal (n)	0	66		

[a] Kappa consistency test.
[b] McNemar chi-square test.

Diagnostic test indicators of EPT and laser Doppler imager in percentage

Both test methods were shown to have 100% sensitivity, 100% negative predictive value, and 0% false negative rate. The specificities of EPT and laser Doppler imager were 85.71% and 94.29%, respectively. The positive predictive values were 58.33% and 77.78%, respectively. The misdiagnosis rates were 14.29% and 5.71%, and the accuracies were 88.10% and 95.24%, respectively (Table 3).

Table of the overall ROC curve

According to the ROC curve and output report, when the total number of teeth in this study was taken as the sample size, the area under the EPT curve (AUC) was 0.94, and the AUC of the laser Doppler imager was 1. This indicated that both methods were excellent diagnostic tools for identification. In this study, the best cut-point values were identified using the ROC curve. When analyzing the data of the laser Doppler imager, it was found that when the cut-point value was 31.55, the sensitivity was 1 and the specificity was 1. According to Youden's index, sensitivity + specificity − 1 closest to one, was the optimal cut-point value, indicating that 31.55 was the optimal cut-point of all samples (Table 4).

Discussion

Since 1960s, owing to the advantages of non-invasiveness and the absence of contact,[16] the Doppler imaging has been

Table 1 Influence of patient-reported symptoms and the professional diagnosis of the dentist on the flux values of the laser Doppler imager and the pulp status 1 year later.

	Mild group		Severe group		*Z*[a]	*P*[a]	*P*[b]
	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)			
Patient complaints	52.17 ± 4.39	53.07 (47.22–55.39)	34.28 ± 15.27	29.35 (23.33–42.70)	−2.03	0.043	0.000
Dental diagnosis	53.81 ± 3.02	54.78 (51.39–56.47)	35.01 ± 11.37	29.97 (26.80–42.70)	−2.37	0.018	0.000

Mild group: patients complained of asymptomatic conditions and dentists diagnosed as mild trauma. Severe group: patients complained of severe symptoms and dentists diagnosed as severe trauma; SD: standard deviation; IQR: interquartile range.
[a] Wilcoxon sign-rank test.
[b] Fisher's exact test.

Table 3 Percentages of diagnostic test indicators of electric pulp test (EPT) and laser Doppler imager.

	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	False positive rate (%)	False negative rate (%)	Accuracy (%)
EPT	100	85.71	58.33	100	14.29	0	88.10
Doppler	100	94.29	77.78	100	5.71	0	95.24

Sensitivity (True positive rate) = True positives/Diseased (a/a + c).
Specificity (True negative rate) = True negatives/Healthy (d/b + d).
Positive predictive value (PPV) = True positives/Positive test results (a/a + b).
Negative predictive value (NPV) = True negatives/Negative test results (d/c + d).
False positive rate: the probability of being determined as diseased based on a diagnostic test when not diseased (b/b + d).
False negative rate: the probability of being determined as not diseased based on a diagnostic test when the person is actually diseased (c/a + c).
Accuracy: percentage of tests being consistent with the results (a + d/a+b + c + d).

Table 4 Table of overall ROC curve: area under the curve (AUC) and optimal cut points of electric pulp test (EPT) and the laser Doppler imager.

	AUC	95% CI	Optimal cut-point
EPT	0.94	0.89–0.99	
Doppler	1	1.00–1.00	31.55

used to measure the blood flow as a useful tool for medical diagnosis and has been widely applied in plastic surgery, assessment of burns and scalds, and diagnosis of peripheral vascular disease.[17] In dental research, the Doppler signals were converted to the red blood cell concentration and fluid velocity in PUs to assess pulp vitality according to the objective data and waveforms.[18,19] According to the literature review, the accuracy rate of the detection of traumatic dental pulp using Doppler was 88.2%. The study believed that the Doppler flowmetry reflected the blood circulation reconstruction of traumatized teeth better than traditional pulp tests.[20]

The diagnosis made by dentists based on the types and evaluation of trauma is significantly correlated with the prognosis.[21,22] In this study, dental diagnoses and patient complaints were evaluated with respect to the flux of the laser Doppler imager and pulp status after 1 year, respectively. As Table 1 shows, significant differences were observed in the flux values of the laser Doppler imager between the severe and mild trauma groups as determined by both the patients' chief complaints and dental diagnoses: the higher the severity of the trauma, the lower the flux value of the laser Doppler imager. Owing to the small sample size of this study, Fisher's exact test was used. The significance was <0.001 which was less than 0.05, indicating that the classification of trauma severity based on the chief complaint or diagnosis was significantly associated with the pulp status after 1 year. These findings were consistent with previous literature, suggesting that the level of fracture, displacement, and symptoms at the time of trauma could indeed be used as predictors of the future prognosis of the tooth.[23,24]

In this study, the specificity of EPT was 85% compared with 94% of the laser Doppler imager, which indicated that EPT was less capable in judging pulp necrosis than the laser Doppler imager, with a higher misdiagnosis rate. However, compared with the previous literature in trauma, the specificity of EPT was 70–90%, and the EPT in this study was still highly diagnostic for tooth trauma, which might be owing to the small sample size. Yet the diagnostic capability of the laser Doppler imager was consistent with the previous literature. For the positive predictive value, when EPT indicated necrosis, the actual rate of necrosis was only 60%. Therefore, the use of EPT to diagnose traumatic pulp required a more conservative interpretation to avoid excessive treatment.[25–27] Finally, the accuracy of the EPT and the laser Doppler imager was tested in this study, and the ratios of the correct diagnosis of the two tests were compared: the accuracy of EPT was 88.10%, and that of the laser Doppler imager was 95.24%, which provided clinicians with a more intuitive interpretation.

As a pilot experiment, when the dental notation was used as the group for statistical analysis, the AUC of the laser Doppler imager was 1, while the diagnostic area of EPT was 0.75–0.92. Both methods had high diagnostic power. Additionally, the best cut-point value of the overall laser Doppler imager was 31.55. However, the blood flow value of the tooth during recovery was often between the necrotic and normal pulps. The closer the value was to the optimal cut point, the more challenging it would be for the dentist to judge. Considering that temporary necrosis is commonly observed in tooth trauma,[28] careful assessments of the pulp and conservative treatment during the early stages of trauma are recommended (Fig. 4).[29]

In this study, the laser Doppler imager model MoorLDI-2λ was used. Appropriate modes of slow scanning may also be selected based on tissue characteristics to obtain accurate images of dental pulp which had low blood flow. As the first study to apply laser Doppler imaging in dental research, there were only seven samples in this study. However, the estimated statistical power was already more than 85%. In the future, the number of samples should be increased to compare the differences between different gender, age groups, and dental positions as well as differences between laser Doppler imager, EPT, and cold test.

In conclusion, both the laser Doppler imager and EPT may be used as tools for diagnosing traumatic pulp necrosis. The laser Doppler imager resolved the dilemma of traditional sensitivity tests. However, considering that temporary necrosis is commonly observed in tooth trauma, it is recommended to carefully assess the pulp and perform

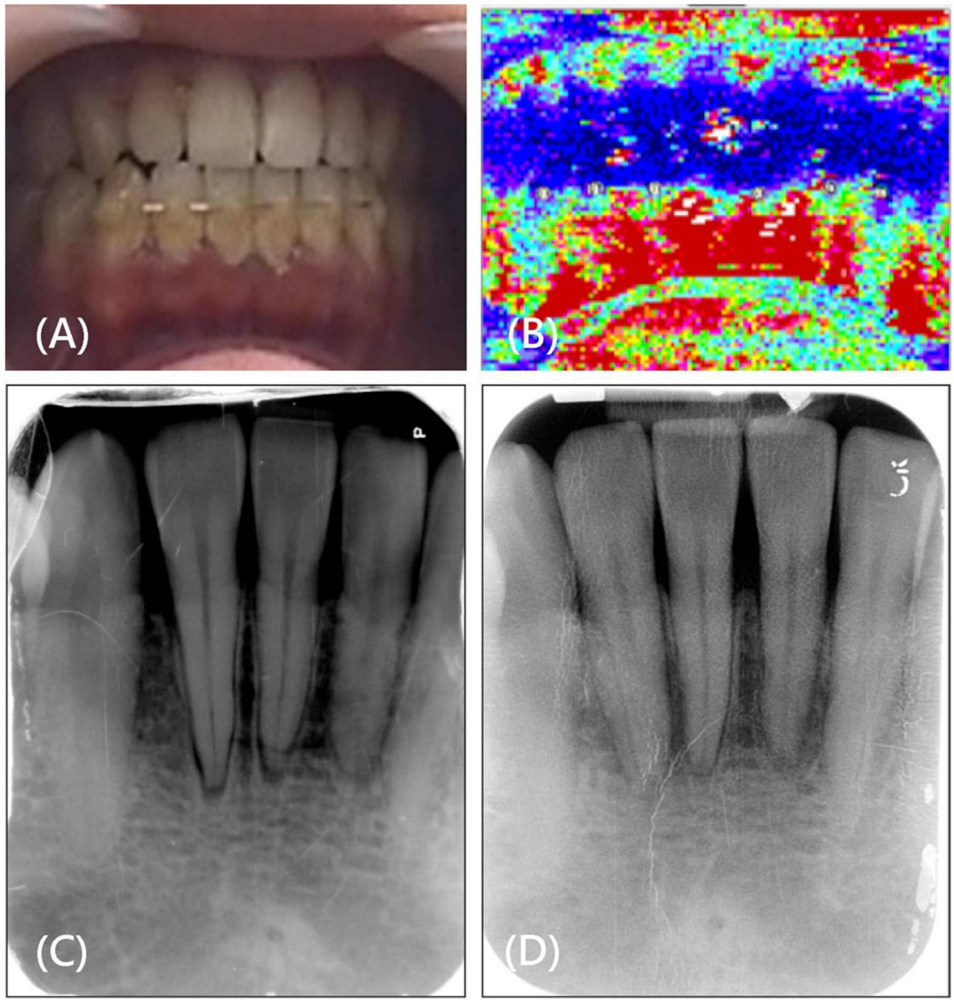


Figure 4 Clinical case presentation. (A) Clinical photograph: there is no response to the electrical pulp test of the mandibular anterior teeth without any symptoms. (B) Laser Doppler imager shows normal blood flow of the lower anterior teeth. Therefore, we advised the patient to postpone root canal therapy (C) Preoperative X-ray showed the root fracture of tooth 31 at the apical third. (D) Follow-up X-ray after three months: the electrical pulp test of tooth 31 still showed no response, but the improvement of the lesion can be observed from the follow-up X-ray, and the root fracture was repaired after angiogenesis.

conservative treatment during the early stage of trauma. Additionally, this study was different from the Doppler flowmetry used in the previous literature and more studies and related training would be required. In the future, more sample data should be used to analyze the best cut points of different tooth positions to provide an appropriate clinical basis for the selection of treatment plans.

Declaration of competing interest

The authors declare no conflict of interest related to this study.

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