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Review Article
บทความปริทัศน์

Laser Doppler flowmetry: basic principle, current clinical and research applications in dentistry

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Abstract

Laser Doppler Flowmetry (LDF) is an accurate and reliable method for assessing microcirculatory function. Several studies have shown that, in comparison with other methods, the measurement of blood flow, especially of blood flow in bones, teeth and surrounding tissues, is reproducible and correlates with clinical features. LDF is typically used in dentistry to evaluate the vitality of a tooth after receiving an injury, such as luxation or avulsion, or the pathological condition of the dental pulp. LDF can be applied to monitor tooth vitality during orthodontic treatment, following maxillofacial surgery that might have possibly damaged the tooth, or in teeth with immature root formation or an open apex in pediatric dentistry patients. In addition, LDF can be used to evaluate osteonecrosis, osteomyelitis, and wound healing or evaluating the stability of dental implants. This review aims to collect the knowledge and advantages of LDF in clinical and research situations. While the implementation of LDF is currently low and confined to academic dental institutions. LDF could become an additional technique for clinical use in dentistry.

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Key words: *laser Doppler flowmeter; oral; tooth vitality*

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Laser Doppler flowmetry

Laser Doppler flowmetry (LDF) is a technique first used for the noninvasive measurement of surface blood flow velocity.[1] LDF uses a continuous wave helium-neon (He-Ne) laser, at 640 nm, as a light source that passes through a fiber-optic cable to carry the light to the surface to be measured. This light is reflected from both the nonmoving skin surface and moving red blood cells, resulting in a "Doppler shifted signal".[1] The Doppler shifted signal is commonly shown as the concentration and velocity (flux) of red blood cells using an arbitrary term "perfusion units" (PU), where the conversion of 2.5 volts of blood flow is equivalent to 250 PU.[2] As red blood cells represent the majority of the moving objects within a blood vessel, the measurement of the Doppler-shifted backscattered light generates the PU values (Fig. 1).

Most current laser Doppler devices give their readout in PUs. PUs are arbitrary and are calculated by the software used by each device. Presently, the commercially available laser Doppler devices cannot determine absolute blood flow perfusion values (e.g. the blood flow in 100 g tissue; mL min^{-1}/100 g^{-1}/tissue).

The major advantages of LDF are that it is noninvasive, and that the measurements can be made continuously. LDF has been widely used in dentistry for several decades to determine the blood flow velocity in the vessels in a tooth in a non-invasive fashion.[3] To record the Doppler shift of the blood cells, both the probe and tooth need to be completely stabilized. Consequently, a stabilizing device made of polyvinyl siloxane or an acrylic splint is usually used. Different types of laser probes, wavelengths, and bandwidths have been studied.[4-6] The greatest disadvantages of LDF lie in technical-related problems, such as the positioning of the probe,[7] methods of isolation of the measured area,[4] and probe design.[8] Systemic conditions such as hypertension can also affect the results. [9]

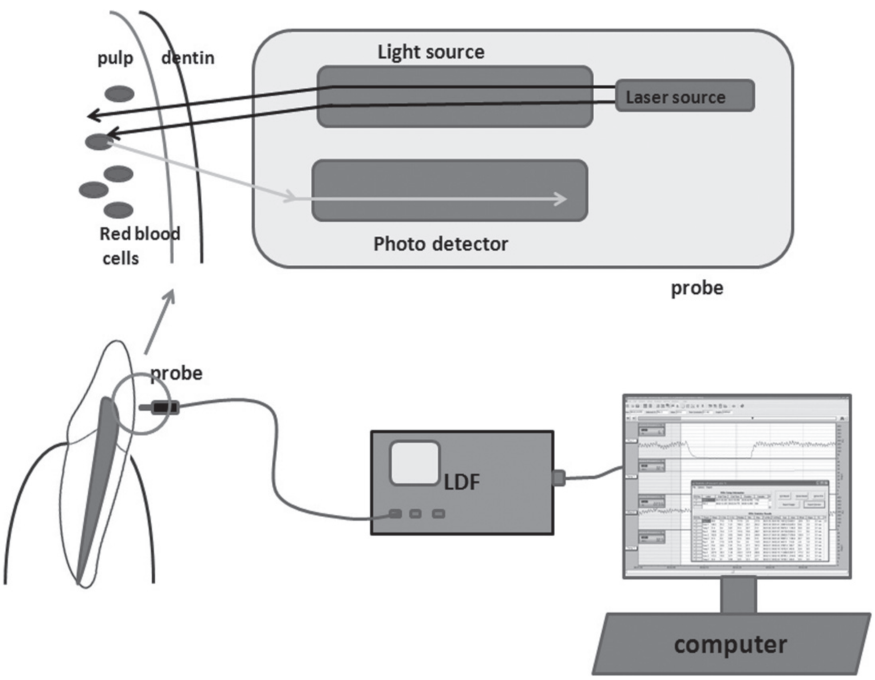

Figure 1. Schematic of the principle of laser Doppler flowmetry

Current uses of LDF in clinical dentistry

Endodontic treatment

LDF is currently used in a number of dental specialties. Its most common use has been to determine the vitality of an injured tooth.[10,11] Recent advances in endodontic treatment have improved the success rate and survival rate of injured teeth.[12] Vascular supply and nerve innervation are currently considered the most accurate determinants of pulp vitality.[13,14] Tests for assessing vascular supply that rely on the passage of light through a tooth have been used as methods for determining pulp vitality.[3] Pulpal blood flow (PBF) measurement using LDF has been described as a more sensitive technique for evaluating tooth vitality compared with conventional methods, such as thermal and electrical pulp testing (EPT),[3] especially in children. Indeed, in pediatric cases, electrical and thermal pulp testing can be painful and the responses can be subjective and unreliable.[15]

Following an injury (e.g. anaesthetized, traumatized, or impacted by orthognathic surgery), a period of denervation of the involved tooth results in the temporary or permanent loss of the tooth's sensory function. This can cause the tooth to be nonresponsive to vitality tests, such as thermal or EPT tests. Up to 8 weeks may be required for a normal pulpal response to return (longer periods of time might be required in older patients because the repair mechanism of the nerve is slower).[16] Ingolfsson *et al.* proposed that the use of LDF could determine the vitality of a tooth because the average pulpal blood flow of a vital tooth is 42% higher than that of necrotic pulp tissue.[17]

There have been many studies of the use of LDF on traumatized or fractured teeth. LDF has been used to investigate the transient ischemic episodes and subsequent revascularization of traumatized teeth.[18,19] LDF has also been used to evaluate the results of the treatment of pathologic teeth.[2] A number of studies have found that pulp necrosis was the most common complication after an avulsion injury.[2,20,21] The decision to perform root canal treatment of the tooth is a major consideration in this type of traumatic injury, which requires prompt and precise treatment to ensure the long term survival of the tooth.[22,23] The avulsion of a permanent tooth is considered the most serious of all dental injuries. Its prognosis depends on the measures taken at the time of the accident or immediately after avulsion.[21] While the replantation of an avulsed tooth should be performed as soon as possible, and is the treatment of choice, this cannot always be done immediately.[24] Periodic evaluation of a replanted tooth by LDF can allow the determination of when root canal treatment is required.

Recently, several studies have proposed a re-classification of tooth injuries. According to Emshoff *et al.*,[24] dental injuries can be classified into different subtypes. These subtypes are described as type I (loss of sensitivity), type II (loss of sensitivity with the presence of periapical radiolucency), and type III (loss of sensitivity, periapical radiolucency, and grey discoloration of the crown). Several studies have indicated that LDF can be one of the tools used to predict the outcome of each injury type based on the decrease in PBF injury (Table 1).[24,25] However, the use of clinical and radiological findings may be needed to supplement the PBF measurements to distinguish between the dental injury subtypes.[24,26-28]

In immature teeth, the revascularization of a necrotic pulp is possible and highly desirable. Unfortunately, current vitality tests are poor indicators of revascularization, commonly resulting in the pulp being unnecessarily removed.[19] In the case of an avulsed permanent tooth with an open apex, the replantation of the tooth should be performed immediately, or it should be kept in an appropriate storage media until replantation can be achieved. In these cases, pulp revascularization should be possible. An avulsed tooth can also be cryopreserved when immediate replantation is not possible.[29] Root canal treatment should be avoided

Table 1 Modified from Emshoff 2004.[2] Classification of tooth injury and its relationship to blood flow as measured by LDF. The table demonstrates the relationships between clinical outcome of the injuries and the blood flow value in 94 patients after 36 weeks follow-up. Incidence of the tooth injuries are shown as number of patients; followed by (percentage). Blood flow (BF) is shown as perfusion unit (PU) with standard deviation (SD). Asterisks indicated statistically difference.

Incidence of diagnostic outcome groups and relationships to blood flow determined by LDF

Diagnostic outcome	Diagnostic criteria	Incidence (%)	BF value (PU)
Absence of adverse outcome	absence of symptom	22 (23.4)	$9.6 \pm 2.1^*$
Presence of adverse outcome			
Type I	loss of sensitivity	72 (76.6)	4.8 ± 4.2
Type II	loss of sensitivity and presence of periapical	35 (37.2)	$7.6 \pm 4.1^*$
	radiolucency	19 (20.2)	2.4 ± 2.3
Type III	loss of sensitivity, periapical radiolucency, and grey discoloration of crown	18 (19.2)	1.8 ± 1.7

PBF, pulpal blood flow; PU, perfusion units. $^*p = 0.000$. Significant outcome group-related difference (number of teeth, n = 94)

unless there is clinical and radiographic evidence of pulp necrosis.[22] LDF is a suitable method for evaluating replanted tooth pulp vitality at different time periods. In this case, LDF can be quite useful in providing the best possible care for children with dental trauma.[30] Revascularization can also be detected earlier by LDF compared to conventional pulp testing methods. This can allow for the avoidance of invasive root canal therapy treatment for the patient if it is not required.[30,31] LDF is also useful for determining the vitality of an autotransplanted tooth, such as a wisdom tooth autotransplanted into an edentulous area.[15,32]

In addition to conventional techniques, LDF can be used to determine the post-surgical healing of periapical lesions after endodontic surgery.[33] In some situations, hyperemia of the dental pulp can occur, due to local inflammation. An autotransplanted tooth can demonstrate transient hyperemia during the initial stages after transplantation (Fig. 2). This results from the acute inflammatory response of the body. This inflammatory process is known to affect the hemodynamics within the pulp and surrounding tissue. In addition, some inflammatory mediators can affect blood flow. Prostaglandins and bradykinin cause an increase of capillary permeability resulting in increased blood perfusion in the tooth and surrounding tissues.[34,35] The use of LDF to detect hyperemic changes can aid in the decision to prescribe anti-inflammatory drugs for the patient.

Orthodontic treatment

LDF has been used for PBF measurement during orthodontic treatment, especially in treatment employing rapid tooth movement.[36-38] In this type of orthodontic case, LDF was reported to be more reliable than the two standard pulp vitality tests, electric pulp testing and the cold test.[38,39] The PBF values of the anchorage

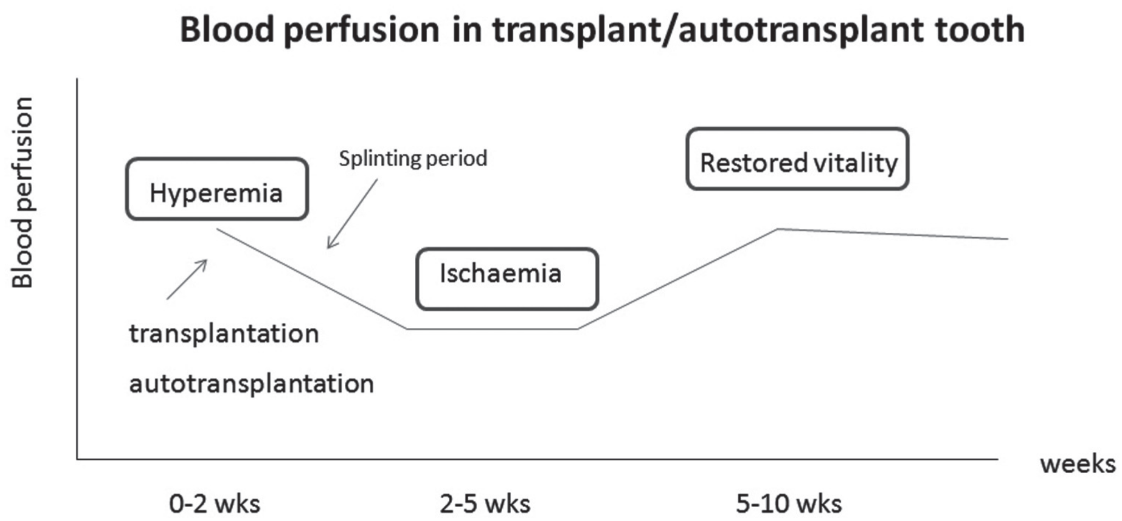

Fig. 2 Blood perfusion changes in autotransplanted teeth assessed by LDF.

teeth rapidly increased nearly two-fold during the first week of the expansion period, followed by a gradual decrease in PBF. However, PBF values returned to normal during the retention period. This effect was proposed to be due to the orthodontic forces applied by the Rapid Maxillary Expansion (RME) appliances, which had caused reversible vascular changes in the pulpal tissue of the anchored teeth. This was further confirmed by histological examination.[36,40] However, it is impractical to measure clinical changes in the pulp of an anchor tooth during orthodontic forces using histological studies. LDF is a noninvasive method and can generate data in real time. Thus, LDF seems to be an appropriate choice for measuring changes in the vascularization of the involved teeth and bone during orthodontic treatment. LDF can also be used to compare the blood flow between the different layers of related masticatory muscles during occlusion.[41]

Oral and maxillofacial surgery

LDF use can be beneficial following surgical procedures that may have affected the vitality of the teeth in the surgical field. For instance, LDF can be used to determine the vitality of involved teeth by measuring the blood flow in the dental pulp after maxillary or mandibular orthognathic surgery.[42-45] LDF was able to demonstrate the vitality of the dental pulp by the presence of blood flow, even though the tooth was transiently unresponsive to electronic pulp testing.[46] LDF has also been used to evaluate the blood flow in soft tissues; such as the measurement of blood flow in a pericranial flap during maxillofacial reconstruction, where good vascular supply in the flap indicates a reduced chance of infection and the potential for good wound healing.[47]

Restorative and Prosthodontic treatment

LDF has recently begun to be used during restorative and prosthodontic treatments; such as the determination implant screw stability. The retention of a dental implant is the most crucial factor in treatment outcome. The use of several modalities are required to ensure the implant's stability.[48] These measurements include mechanical evaluation, such as insertion torque assessment, implant stability quotient, and resonance frequency analysis (scanning laser Doppler vibrometer). Riecke *et al.* used LDF as one of the biomechanical parameters in the *in vivo* evaluation of implants.[49] LDF has further been employed to assess the vascularity of the area of bone planned for implant placement in patients receiving radiation prior to dental implant fixation. Local blood flow in the bone is of clinical significance in preventing early implant loss and in reducing the risk of osteoradionecrosis.[50]

Disadvantages and limitations

The size and extent of tooth restorations, such as amalgam fillings or a fixed prosthesis can have a meaningful effect on PBF determination.[51] LDF can also be sensitive to distortion from the blood flow in adjacent tissues. Extra-pulpal signals, principally from periodontal blood flow, may distort the signal. In addition, local inflammation in the dental pulp can extend into the adjacent periodontal tissues and alter the PBF value.[52] Thus, the use of a proper barrier (such as a dark color rubber dam) is required.[3,53,54] LDF is also susceptible to extraneous noise, such as loud sounds (i.e. vibrations) or movement near or in the apparatus itself.

Taking a measurement from an appropriate baseline tooth is an important factor when comparing the change in PBF over time in each patient. In routine use, contralateral incisors, canines, and premolars are usually reliable as intra-patient controls for each PBF measurement.[55] However, not every case allows for such baseline control, because the contralateral tooth may already be restored, crowned, or have received root canal treatment. Thus, the identification of the proper baseline control tooth can be a challenge.

The cost of the LDF equipment makes it unlikely that, outside of an academic dental environment, LDF will become a popular or widely used technique in the near future.[53,56] It should be noted that the use of this method may be contraindicated in teeth with vital apical pulp tissue following pulpotomy, because LDF probes only detect coronal PBF.[57] Some systemic conditions have been reported to affect blood flow detection by this method. Menstruation or alteration in estrogen levels in women can decrease pulpal blood flow, which may occur because of changes in the total blood volume in the entire body.[58]

Considerations for LDF use in clinical applications

- *Light source in LDF machine*

The first LDF apparatus used a 2 mW He-Ne (630 nm) laser and became commercially available as the Periflux^R laser Doppler flowmeter (Perimed AB, Sweden). In Europe, this type of laser Doppler was the first to be sold in larger numbers and became the most widely used laser Doppler perfusion monitor in 1990s. Later, the 5 mW laser diode with an infrared wavelength of 780 nm has been developed (TSI Inc, USA; Vincent Medical, UK). The advantages of the laser diode are its lower cost and small size and it requires less power voltage. The disadvantages are a less stable emission spectrum, dependency on temperature of the diode while the output of light can be influenced by backscattering. "The Moor laser Doppler flow monitor" (Moor Instruments, UK) used a 3 mW semiconductor laser diode (780-810 nm) and a single photodetector system in combination with optic fibers to conduct light to and from the tissue. This Moor LDF was the first dual-channel device that combined two laser doppler flowmeters in one apparatus.[5,59] Between the 780 nm and 630 nm, it was reported that the diode laser showed good sensitivity, but poor specificity, and that the 630 nm wavelength showed good specificity, but poor sensitivity.[5,60]

Most of the current LDF machines available use a 830 nm diode semi-conductor laser light source (Moor, UK, Biopac, USA, ADinstrument, USA) or He-Ne laser at 630 nm (Coherent, USA). Other types of laser sources, such as an Nd/YAG laser was not suggested as the primary LDF light source due to its longer wavelength (1064 nm), which could intensify a false positive or background noise.[61]

- ***Probes***

Currently, there are many types of probes available; skin, needle, and endoscopic, depending on its intended use. Most of the LDF measurements in dentistry have been performed using a needle type probe. A needle probe can be used for surface measurements, inserted into tissue, or used for single vessel measurements. The needle design also lends itself to taking measurements in tissues with restricted access, including teeth and bone. The length and angle of the probe used also varies according to the measurement site. For example, the probe used in measuring pulpal blood flow is usually a stainless steel tube needle that is 10-80 mm in length, with a 1.5 mm external diameter. The other probes, such as endoscopic probes (deep soft tissue measurement) and skin probes are also available, but were less used in dentistry (Fig. 3). It has been reported that the

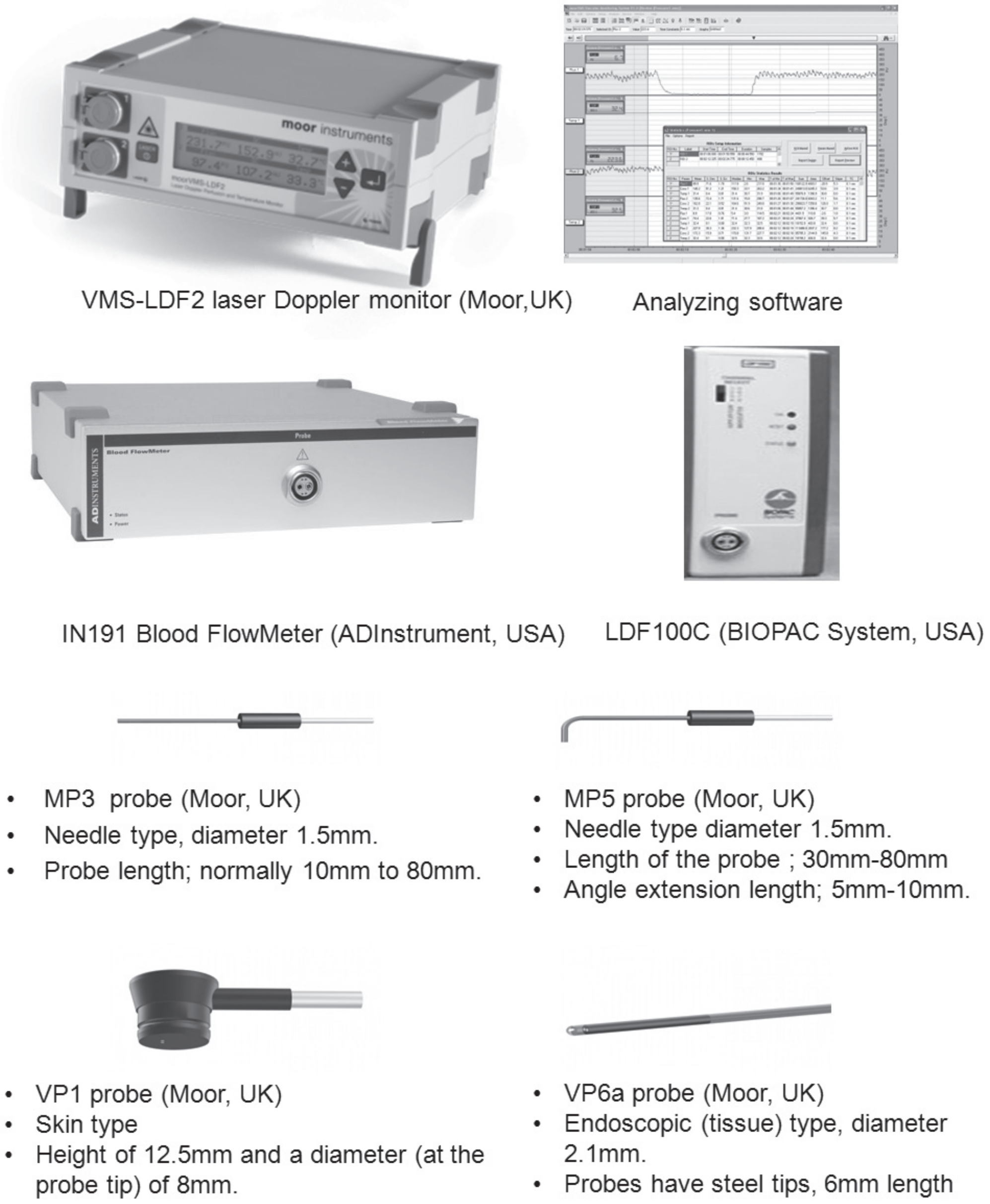

Fig. 3 Examples of the currently used LDF and some probes. (with permission) angulation or the length of the probe did not alter the pattern of the laser emission.[61] It was suggested that the probe should be placed on the cervical third of the tooth because this minimizes backscattering. However, it was also observed that the value of the flux increased when the probe was placed closer to the gingival tissue.[62]

Because the probe has to be stabilized during the entire measurement period, a suitable device to hold the probe in the correct position is needed to maintain the required distance from the tooth surface and to ensure that the probe is positioned in the same location during follow-up procedures. A wide variety of holders can be used to position the LDF probe.[3] Most studies suggest that a silicone or polyurethane splint with rubber dam isolation is the most efficient method.[63]

Since the LDF method generates the flux value in PUs, which are arbitrary units, it is difficult to obtain a normal average of each tooth, which may differ at multiple measurements. While most of the studies on LDF have focused on anterior teeth, it has been reported that there was no statistical association between value obtained from LDF and tooth type,[64] with non-vital teeth showing lower PBF values, but not as low as zero.

- ***Avoiding undesirable signals***

Extra-pulpal signals or signals from the surrounding environment, such as periodontal tissues, can lead to an inaccurate determination of the flux value. Thus, proper isolation with a dark/opaque rubber dam is highly suggested. Moreover, the same tooth in the contralateral quadrant of the same dental arch is the most suitable control, unless it has been heavily restored with metal fillings or a crown.

Prior to LDF examination, patients should rest in a supine position in the dental chair for approximately 10 minutes. Blood flow data should be collected for at least 3 minutes at each measurement session. The temperature of the room should be constant. Patients should avoid or minimize their movement. It is also recommended to record the patient's pulse rate and blood pressure during the measurement.[2]

Current use of LDF in dentistry-related research

The use of LDF for blood flow measurement was first established in a study of retinal vessels in rabbits in 1972.[65] The optical fibers and photodiode in the detection unit were developed in 1977.[1] A special double

Table 2 Summary of the advantages and disadvantages of LDF.

Usage of laser Doppler flowmetry	
Advantages of LDF	**Limitations of LDF**
1. Effective and reliable evaluating dental pulp vitality, particularly in teeth with immature root formation and open apex.	1. Data might be misinterpreted by the effect of surrounding circulation such as gingival or oral tissues.
2. Useful in cases of impact injury where the blood supply remains intact but the nerve supply is damaged.	2. Difficult to measure in the teeth with large restorations, such as metal inlay, crown or orthodontic brackets.
3. Non-invasive and painless.	3. Requires individual stabilizing devices (such as; splint, rubber dam or silicone).
4. LDF can be reproducible and the data can be analyzed later.	4. Costs might be discouraging for routine clinical use in an average dental office.

channel system was later developed to reduce the noise and back-scatter signals.[66] The first LDF measurement in humans was performed in Switzerland in 1985 in a study of femoral osteonecrosis patients.[67]

The research use of LDF in dentistry dates back to the early 1990's with several studies by Matthews and Vongsavan.[56,60,68] LDF has been used as a measurement pre-and post-delivery of drugs and medications, such as capsaicin or desensitizing agents, into the teeth and surrounding oral tissues.[69,70] LDF can be used in studies involving rats, pigs, cats, and dogs, which are the preferred animal models in drug development. This can predict the effect of a treatment or material if it were given to a human.[31,71-75] The evaluation of angiogenesis in a wound flap can be done using LDF monitoring. In addition to the study of microcirculation, extensive LDF studies have been performed on chronic ischemic ulcers and wound healing; such as diabetic foot ulcers and ischemic pressure sores in hind limb ischemic models.[76] Monitoring the oxygen saturation at an ulcer or tumor site after receiving hyperbaric oxygen might be another clinical research use for LDF

Materials used in dentistry (such as methacrylate resin, clove oil, dental alloys, or dental gloves) can penetrate the skin and cause damage, local inflammation, and irritation. During skin irritation, sub-epidermal blood flow changes occured, which can be assessed using LDF monitoring.[77]

The assessment of skin irritation via the scoring of erythema using "the patch test" is common. However, mild to moderate irritation may not result in differences sufficient to be visibly observed, as is required for a positive score. As a result, studies of skin irritation and allergy typically rely upon a combination of measurements. These include trans-epidermal water loss, erythema scoring, histological assessment, and skin blood flow monitoring.[78] LDF monitoring is suggested for use when mild to moderate irritation is present and the irritation may not be visually apparent and where erythema scoring would not be positive.[79]

Conclusion

In conclusion, the use of LDF is well established in many fields of Dentistry due to its advantages of being non-invasive, easily repeated, and reliable in identifying the vitality of the dental pulp compared to other methods. There are a number of studies of LDF use in Pediatric Dentistry, Orthodontics, Oral Surgery, and Prosthodontic Dentistry. However, LDF use has been limited to dental schools in research studies rather than clinical use due to its cost and complicated procedures. These difficulties in procedures or costs could be reduced if the machine is used by the staff of multiple departments. It is hoped that this review article will encourage dental practitioners in various specialties to use LDF as an additional technique in clinical dentistry.

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เครื่องเลเซอร์ดอปเปลอร์โฟลว์มิเตอร์: หลักการและการใช้งานในทางทันตกรรมและงานวิจัยในปัจจุบัน

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บทคัดย่อ

เครื่องเลเซอร์ดอปเปลอร์โฟลว์มิเตอร์ เป็นเครื่องมือในการวัดการไหลเวียนของโลหิตระดับไมโครซึ่งมีความแม่นยำสูงในงานวิจัยเมื่อเปรียบเทียบกับวิธีอื่นๆ การศึกษาหลายแห่งใช้เครื่องเลเซอร์ดอปเปลอร์โฟลว์มิเตอร์เพื่อวัดการไหลเวียนของโลหิตในบริเวณฟัน กระดูกและเนื้อเยื่อรอบข้าง มีความสามารถในการทำซ้ำได้และสอดคล้องกับลักษณะทางคลินิก การประยุกต์ใช้เครื่องเลเซอร์ดอปเปลอร์โฟลว์มิเตอร์ในทางทันตกรรมที่แพร่หลายที่สุดในปัจจุบันคือการใช้ประเมินสภาวะความมีชีวิตของฟันภายหลังจากการได้รับอุบัติเหตุหรือภยันตราย ได้แก่ การเคลื่อนที่ของฟันในกระดูกเบ้าฟัน การหลุดของฟันออกจากเบ้าฟันหรือพยาธิสภาพของเนื้อเยื่อในฟัน เป็นต้น การประยุกต์ใช้เลเซอร์ดอปเปลอร์โฟลว์มิเตอร์ ในทางทันตกรรมอื่นๆ ได้แก่ การประเมินสภาวะฟันในระหว่างการเคลื่อนฟันในผู้ป่วยที่ได้รับการจัดฟันหรือการรับการรักษาทางศัลยกรรมบริเวณขากรรไกรและใบหน้าซึ่งอาจส่งผลให้เกิดการบาดเจ็บต่อฟันบริเวณดังกล่าว นอกจากนี้ยังใช้ประเมินสภาวะฟันในผู้ป่วยเด็กที่ปลายรากยังไม่ปิดหรือยังสร้างไม่เต็มที่ บางการศึกษาทางคลินิกได้นำเลเซอร์ดอปเปลอร์โฟลว์มิเตอร์ มาประเมินสภาวะการอักเสบและการตายของกระดูก รวมไปถึงการประเมินเสถียรภาพของรากเทียมในขากรรไกรอีกด้วย โดยบทความปริทัศน์นี้มีจุดมุ่งหมายในการรวบรวมความรู้และประโยชน์ของเลเซอร์ดอปเปลอร์โฟลว์มิเตอร์ในทางทันตกรรมและงานวิจัย ปัจจุบันการใช้เลเซอร์ดอปเปลอร์โฟลว์มิเตอร์ ในทางทันตกรรมยังไม่เป็นที่แพร่หลายและจำกัดอยู่เพียงงานวิจัยในสถาบันการศึกษา อย่างไรก็ตามเลเซอร์ดอปเปลอร์โฟลว์มิเตอร์เป็นเครื่องมือที่มีความแม่นยำสูงและเชื่อถือได้ในการใช้วินิจฉัยโรคสภาวะของฟันและกระดูก จึงน่าจะมีการนำเลเซอร์ดอปเปลอร์โฟลว์มิเตอร์ มาใช้ในงานทันตกรรมให้แพร่หลายมากกว่านี้

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