The Saudi Dental Journal (2023) 35, 423–436

King Saud University

The Saudi Dental Journal

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REVIEW ARTICLE

Recent development of photoacoustic imaging in dentistry: A review on studies over the last decade

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Received 3 January 2023; revised 15 May 2023; accepted 17 May 2023
Available online 23 May 2023

KEYWORDS

Photoacoustic imaging;
PAM;
PAT;
Dental caries;
Periodontal disease;
Oral disease

Abstract *Background:* This work performs a literature review of photoacoustic imaging (PAI) in dentistry and discusses the development of PAI in relation to oral health.

Methods: A search method was used to locate papers published between 2011 and 2023 in Google Scholar and PubMed databases, and 25 studies were selected. Reports on PAI in dentistry were included. Articles not written in English or whose full text could not be accessed were excluded. The remaining publications were checked and evaluated to determine whether they contain supportive materials for PAI in dentistry.

Results: The majority of articles about PAI in dentistry are associated with caries studies. Photoacoustic microscopy is the most commonly utilized PAI system. PAI studies generally focus on ex-vivo investigations using extracted human teeth. The acoustic signal obtained from carious teeth is greater than that obtained from normal teeth. In addition to imaging oral soft tissues from animal models and the periodontal pocket depth in human volunteers, PAI is applied to evaluate dental implants and oral biofilms.

Conclusion: There have been numerous investigation on PAI in dentistry, but it is not yet applicable in dental practice. In the future, PAI studies are expected to contribute to the invention of an alternative non-ionizing imaging technology that is comfortable for patients, user friendly, and capable of providing reliable information at a reasonable cost.

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https://doi.org/10.1016/j.sdentj.2023.05.013
1013-9052

Contents

1. Introduction

The most frequently encountered problems in dentistry are oral, dental, and maxillofacial pathologies. Several examples include tooth fracture, tooth resorption, dental caries, periodontal and gingival diseases, and missing teeth. Oral disorders, such as undetected tooth decay, severe periodontal disease, and edentulism, damage up to 3.5 billion individuals globally (Kassebaum et al., 2017). In addition, periodontal diseases affect up to 90% of patients (Niemiec and Diplomate, 2018). Based on this condition, nearly every patient has had some kind of oral or dental problem. For humans, these conditions can cause mild to severe pain (Niemiec and Diplomate, 2018). Oral health is also being a major concern for veterinarians. Approximately 10% of dogs and 40% of cats suffer from tooth resorption as a result of fractured tooth pulp exposure.

Imaging techniques, such as magnetic resonance imaging (MRI), ultrasound (US) imaging, computed tomography (CT), and x-ray imaging, have been adopted to support diagnosis and treatment in dental practice (Kocasarac and Angelopoulos, 2018; Tymofiyeva et al., 2013). However, current imaging systems have confines due to the use of ionizing radiation, low sensitivity, low spatial resolution, bulkiness, inconvenience, slow image acquisition, and unaffordable costs (Lee et al., 2015).

Photoacoustic imaging (PAI) is a non-invasive biological imaging technique that unifies the benefits of optical and sound imaging (Dahlstrand et al., 2020). The photoacoustic effect, which is the basic principle of PAI, involves illuminating a substance or tissue with an modulated laser wave. The tissue absorbs the light pulse, resulting in thermoelastic expansion and consequent wave propagation. PAI is distributed into two subfields: photoacoustic microscopy (PAM) and photoacoustic tomography (PAT); the latter of which allows for in-vivo imaging. Using an array detector, the produced acoustic waves from the medium's surface can be detected in PAT. The distribution of tissue optical absorption illuminated by laser in PAI is then calculated for image reconstruction using the sound waves received from the detector. With simple changes, beamforming algorithms and techniques frequently employed in ultrasound (US) imaging can be applied to PAI (Paridar et al., 2019).

The capabilities of PAI have been demonstrated in numerous applications, including hemoglobin oxygen saturation, cancer imaging, tumor identification, carcinoma, and blood vessel imaging (Dahlstrand et al., 2020; Duong et al., 2022; He et al., 2017; Hennen et al., 2015; Martinho et al., 2019). Thus, PAI in dentistry is expected to be a non-invasive, radiation-free mode of dental and oral examination with high spatial resolution, rapid image acquisition, and affordable cost (Cheng et al., 2022; Erfanzadeh et al., 2018; Hariri et al., 2017; Widyaningrum et al., 2018, 2020; Yao et al., 2017; Zhang et al., 2018). PAI is a new imaging method that improves the quality of medical and dental care by providing essential compositional information and complements existing clinical imaging modalities (Sangha et al., 2018). Given the advancements in the application of PAI in dentistry and its positive impression, this review aims to provide a fresh viewpoint on the use of this method in dentistry.

2. Materials and methods

2.1. Literature search

This review was conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines) and drew data from two databases, Google Scholar and PubMed (Fig. 1). A literature search was directed using a number of keywords, namely, PAI, dentistry, dental, and periodontal. Boolean operators, i.e., "AND," "OR," "()," and "," were also employed to facilitate the search, and the following keywords were formed: dental AND laser, dental OR periodontal OR caries OR periodontitis, "photoacoustic imaging," and (photoacoustic imaging for dental).

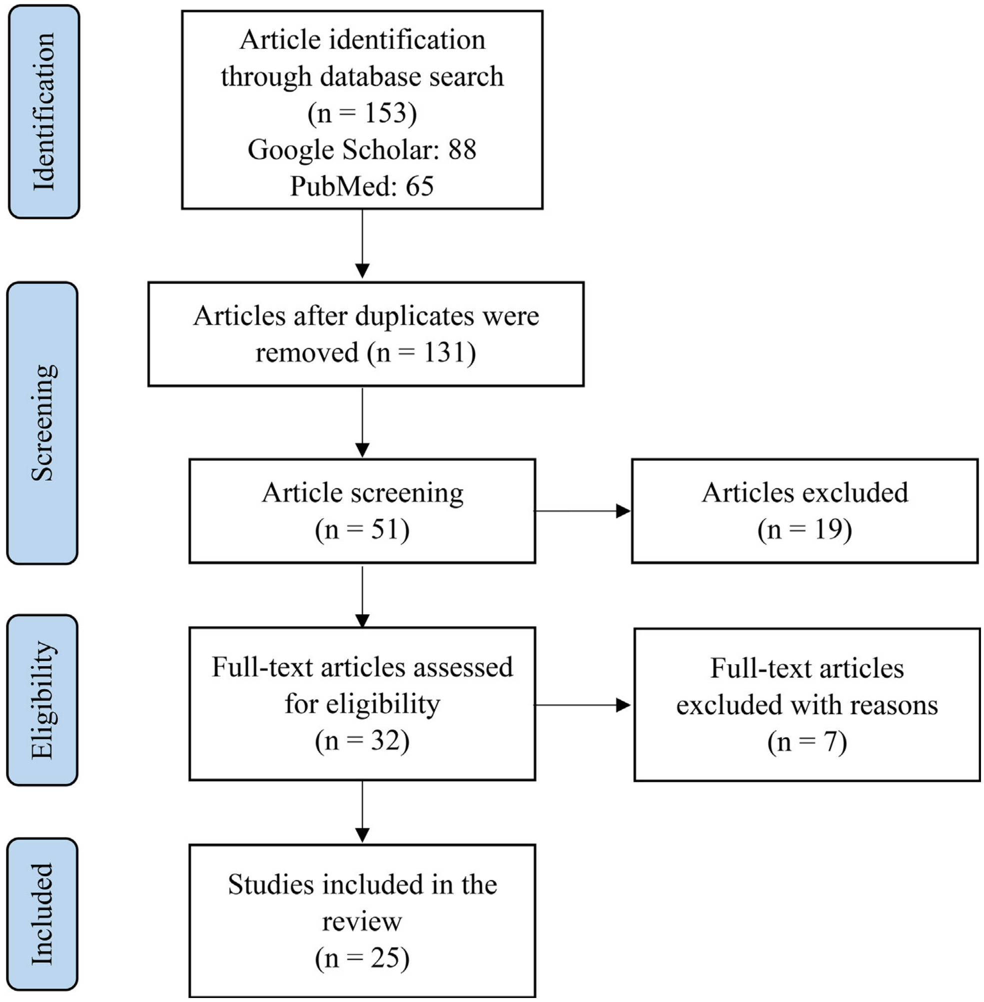

Fig. 1 Flowchart of literature search.

2.2. Inclusion and exclusion criteria

Initial evaluation was conducted by identifying the titles through literature search. If the title indicated that the abstract might be included, then the abstract was reviewed. In the event of doubt, the entire article was read. After the abstracts were evaluated, the articles deemed eligible for review were identified, and the full-text articles were evaluated. If an article satisfied all of the requirements listed below, then it was included in the compilation: study on PAI in dentistry (including human subjects' ex-vivo, in-vivo, and clinical uses) published since 2011 to March 2023. Articles not written in English or whose full text could not be accessed were excluded. The included studies were evaluated and then organized in tables by authors/year, study purpose, laser settings and procedures, objects/samples, and brief summary of results.

3. Results

3.1. Search outcomes

The initial screening (title and abstract review) of Google Scholar and PubMed generated 153 articles. After duplicates were removed, 131 articles were included. Among which, only 51 were selected on the basis of exclusion criteria. During the process, 19 articles were further excluded, and 32 articles were subjected to a full-text review for eligibility assessment. An additional 7 articles were excluded during the process. Finally, this review included 25 papers. Fig. 1 illustrates the literature search and selection used in this review.

3.2. Study characteristics

This review comprised 25 studies published between 2011 and 2023. Table 1 summarizes the data taken from the selected studies. Most studies focus on the ex-vivo application of PAI for the detection of tooth decay (Arabpou et al., 2019; Cheng et al., 2016; El-Sharkawy and El Sherif, 2012; Khosroshahi and Valizadeh, 2020; Koyama et al., 2018; Li and Dewhurst, 2016; Periyasamy et al., 2018; Rao et al., 2011; Sampathkumar et al., 2014; Silva et al., 2021; Tasmara et al., 2023; Yamada et al., 2016). In general, clinical studies of PAI in dentistry assess the pocket depth of periodontal tissues from humans (Fu, Khazaeinezhad, et al., 2022; Fu, Ling, et al., 2022; Fu et al., 2021; Lin et al., 2017; Moore et al., 2018, 2022; Mozaffarzadeh et al., 2021), and ex-vivo investigations employ samples from human teeth (Alifkalaila et al., 2021;

Table 1 Summary of publications on photoacoustic in dentistry.

Authors (Year)	Study Purpose	Laser Settings and Methods	Objects/Samples	Outcome	Comparison
Rao et al. (2011)	PAM to detect dental caries or diagnose the vitality of the dental pulp, which is the innermost part of the tooth, containing the nerves, blood vessels, and other cells.	Pulse width: 6.5 ns, 6.5 ns, and 15 ns. Wavelengths: 570 nm, 570 nm, and 804 nm. Pulse energies: 40 nJ, 0.8 nJ, and 60 mJ. A 75 MHz acoustic transducer.	Dental tissues of extracted teeth from humans (ex-vivo).	Photoacoustic amplitude from dental caries higher than healthy teeth.	Monitoring variations in the PA signal over time is required to determine the progression of caries since surface from deeper dental tissue may have an impact on the relative PA signal distribution. PAM is a potential method for visualizing pulp and tooth decay.
El-Sharkawy et al. (2012)	The laser generation of surface acoustic wave (SAW) technique to investigate the mechanical and acoustic properties of human teeth.	Q-switch Nd:YAG laser excited SAW pulses. Pulse width: 10 ns Pulse energies: 2 mJ. The interferometer used an He–Ne laser (10 mW, 632.8 nm).	Normal and caries teeth extracted from humans (ex-vivo).	The normal tooth's and caries' thermoelastic expansions were 0.3 µs and 1.3 µs, respectively.	Spontaneous sound wave pulses can usually be tracked in tissues with laser pulse intensities below the cut-off for elimination in the thermoelastic system, due to the effective laser excitation of SAWs. The approach is therefore both non-contact and non-destructive.
Sampathkumar et al. (2014)	A non-contact optical technique for the imaging and detection of early-stage dental caries.	Nd:YAG laser (532 nm) with the Michelson interferometer. Pulse duration: 5 ns at 10 Hz. Pulse energies: 25 mJ/pulse.	Extracted teeth from human were preserved in thymol-buffered saline to inhibit bacterial development (ex-vivo).	Samples with lesions generated a higher PA signal than healthy teeth.	An effective device for identifying tooth decay is the All-Optical PAI (AOPAI) system. The technology differs from conventional ultrasonic techniques in a number of ways, including a higher signal between healthy and decayed teeth and the absence of an intermediary between the source and the molar.
Cheng et al. (2016)	Early dental lesions are detected using dual-contrast photoacoustic computes.	An 80 mJ Q-switched Nd: YAG laser (532 nm, 8 ns, 10 Hz. Ultrasound transducer with 4,39 MHz.	Both healthy teeth and a sample of tooth lesion from humans (ex-vivo).	B-mode PAT provides a detailed image of tooth morphology and macrostructure. S-mode detects early tooth lesions.	The early dental lesions cause changes in tissue characteristics that are detectable by the system. Early dental lesions can be accurately identified by a thorough review of the dual-contrast information.
Li et al. (2016)	A near-infrared photoacoustic probe for detecting early tooth illness.	Nd:YAG laser pulses (1064 nm, 8 ns). The power of the 2 Hz laser is 12 mJ/pulse. Ultrasound transducer 1–5 MHz.	A phantom human tooth with dental caries (ex-vivo).	The PA signal generated from dental caries is 10 times stronger than the healthy tooth.	With the high sensitivity of PA imaging, periodontal diseases with morphological alterations in both soft and hard tissues can be detected on first stage. To increase the imaging speed, an array probe design is suggested.
Yamada et al. (2016)	Two lasers and a US sensor placed on the tooth's surface detected PA signals from	Nd:YAG laser (1064 nm and 532 nm) Pulse width: 1.2 ns Pulse	An incisor tooth extracted from human beings (ex-vivo).	Teeth with blood in the pulp cavity emit high-frequency ultrasonic vibrations.	The impact of absorption in tooth pulp is plainly visible in maps of frequency bands acquired by

Table 1 (*continued*)

Authors (Year)	Study Purpose	Laser Settings and Methods	Objects/Samples	Outcome	Comparison
	hemoglobin in oral tissues.	rate: 1 mJ/pulse at 100 Hz. Ultrasound transducez 6 MHz.			performing quick Fourier transforms.
Lin et al. (2017)	PA ultrasound is used to depict probing levels with high spatial precision.	Vevo LAZR system (680-970 nm). US transducer (21 and 40 MHz).	39 pig molars were treated with a contrast agent (ex-vivo).	PAI approach, which is based on the PA signal, provided 0.01 mm precision and could cover the entire pocket.	Photoacoustic imaging for probing depth measurements has potential for dental applications. The findings achieved with this novel method were very comparable to the conventional periodontal probe technique. The accuracy was higher, with better quality images encompassing all areas of the tooth. Moreover, gingival thickness can be easily evaluated.
Lee et al. (2017)	Ex-vivo PAI of dental implant was demonstrated.	Nd:YAG laser (1064 nm). Laser pulsed: 5 ns/10 Hz. A focused ultrasound transducer 5 MHz.	Animal tissue was used to simulate an implant, jawbone, tooth, and soft tissue (ex-vivo).	PAI was used to generate a photoacoustic image of the implant and teeth in the jawbone, which was covered by 10 mm of animal tissue.	PAI is able to be used to evaluate soft tissue and bone anatomy, as well as validate the position and depth of the implant fixture.
Dias et al. (2018)	Photoacoustic spectroscopy monitors and analyzes biofilm plaque on human tooth enamel samples.	A 900 W xenon arc lamp with 350–900 nm (UV–VIS) and 900–2200 nm (NIR-MID infrared). Modulation frequency: 20 Hz. A microphone as a detector.	Human premolar teeth enamel samples were sliced and placed in the buccal area (ex-vivo).	Oral biofilm development on the tooth is shown at 410 nm, excitation from 1450 to 1550 nm, intensity rise about 1920 nm.	Plaque can be spotted using photoacoustic spectroscopy due to bactericidal effect on enamel. Detecting biofilms is possible utilizing compact monitoring device that excite Soret-band LED light with a brief exposure period.
Koyama et al. (2018)	A PAI system based on optical fibers for identifying tooth decay.	A laser (532 nm) and an US transducer as a detector.	Models of caries were made using a coloring agent with an absorbance pattern similar to the design of true caries lesions (ex-vivo).	Frequency at 0.5 MHz–1.5 MHz, PA wave intensities are higher in pigmented tooth regions.	A photoacoustic technique that uses various polarization angles to find lesions without brown area on tooth surface. The radial back-propagation technique, for example, is required to improve imaging precision for the identification of more subtle lesions.
Moore et al. (2018)	PAI detects periodontitis and monitors gingival health non-	Nd:YAG laser (680 nm, 5 ns, 20 Hz). Transducer with a	A healthy volunteer provided 10 teeth (teeth 7–10, 22–27) and	Based on the PA signal, the volunteer had excellent dental	The technique allows dental practitioners to replace conventional

(*continued on next page*)

Table 1 (*continued*)

Authors (Year)	Study Purpose	Laser Settings and Methods	Objects/Samples	Outcome	Comparison
	invasively.	rectangle linear grid.	soft tissues (in-vivo).	hygiene no pockets deeper than 4 mm.	probing in favor of photoacoustic image-guided examinations. The creation of a small, PA-US mouth as a tool for rapidly and non-invasively gathering crucial periodontal data.
Periyasamy et al. (2018)	Photoacoustic tomography and PAM system use to detect dental caries, cracks and lesions.	Nd:YAG (1064 nm) at 10 Hz, 5 mm beam diameter. US transducer (2.25 MHz) as a detector.	Extracted teeth from human that are divided in the sagittal and transverse planes (ex-vivo).	Caries demonstrated unusual mineral distribution and increases PA signal compared to regular teeth.	PAT and PAM images tooth lesions and caries. The PAT system can only image teeth. However, a portable PAM devices that already being used in dermatology can be further developed to image teeth and the oral cavity using extraoral transducer. The PAM system with acoustic resolution that is being proposed here is not yet applicable in the medical field.
Widyaningrum et al. (2018)	PAI systems for imaging oral soft tissue (rat tongue).	As an excitation source, PAI used a intensity-modulated continue-waves diode laser (532 nm, 200 mW). A condenser microphone as a detector.	This study used sagittally-sliced tongues from Sprague-Dawley rats as oral soft tissue samples (ex-vivo). Sample embedded into plasticine as the surrounding medium.	Plasticine produces a different PA signal than biological tissue, particularly oral soft tissue. Photoacoustic emissions from the soft oral tissue generates higher acoustic intensity.	The study proved that imaging oral soft tissue using a modulated continuous wave of diode laser and condenser microphone is technically feasible. The optimal intensity to imaging oral soft tissue must be maintained.
Arabpou et al. (2019)	Early dental caries detection using photoacoustic signals	As an excitation source, PAT used a laser pulse with 633 nm. Ultrasound transducer to detect the photoacoustic signal.	Phantom teeth samples with both wide and small lesions (ex-vivo).	A broad lesion absorbs an average of 0.0508 W/m^2, while a small lesion absorbs an average of 0.0267 W/m^2.	The target area must get more energy and pressure to be detected accurately, while the surrounding area must not be exposed to laser light to avoid the risk of tissue damage.
Khosroshahi et al. (2020)	The reactions of the pulse Nd: YAG laser with healthy and carious tooth tissue, as well as amalgam, are studied using a PA sensor and laser-induced plasma spectroscopy.	Nd: YAG laser (1064 nm, 7 ns). Polyvinylidene fluoride (PVDF) piezoelectric polymers transducer as a sensor	Mandibular third molar (wisdom teeth), ex-vivo.	PA signal of carious dental tissue is higher than healthy. The fluence increases the amalgam acoustic intensity. This is due to the high absorption of the laser intensity by the amalgam.	Plume and ionized products, whether inhaled by a dental professional or the patient, can cause health problems once deposited in the respiratory tract. From a safety perspective, it is critical to consider the biophysical interaction of laser with dental amalgam.
Widyaningrum et al. (2020)	PAI is a technique used to study the impact of laser modulation of intensity on the quality of PA images.	A diode laser (532 nm, 200 mW) was used in the PAI system. Condenser microphone as a detector	Oral soft tissue samples were taken from the tongues of animals and placed in a 10% formalin (ex-vivo).	PA images of paraffin-fixed sample have higher quality than direct images of oral soft tissue that have not been paraffin-embedded.	The study reveals the viability of PAI technique using a diode laser to image oral soft tissue by applying intensity modulation at a single

Table 1 (*continued*)

Authors (Year)	Study Purpose	Laser Settings and Methods	Objects/Samples	Outcome	Comparison
					frequency. The PAI system's components and imaging method must still be developed.
Alifkalaila et al. (2021)	PAI for the characterization of dental anatomy.	532 nm diode laser. Condenser microphone as a detector	Extracted teeth from human (ex-vivo).	The highest acoustic intensity generated by the pulp indicates that the chromophores of the innermost dental layer are superior to those of the outer layers.	A simple PAI system can image dental anatomical structures. Investigating the use of photoacoustic imaging for other dental tissues requires further research.
Silva et al. (2021)	This study used visible and near-infrared wavelengths to detect dental caries.	Nd:YAG laser (532 nm and 1064 nm, 6 ns, 10 Hz. US transducer 5 MHz as a detector.	15 permanent molars (5 sound, 5 incipient, and 5 advanced caries) (ex-vivo).	At 1064 nm, the maximum PA signal intensity is twice that of 532 nm. This indicates that compared to visible light lasers, near-infrared lasers create stronger photoacoustic effects.	The handheld integrated PA system used in this study is entirely automated and has actual clinical applications with the ability to fit inside the oral cavity.
Fu et al. (2021)	Food-grade contrast agent (cuttlefish ink) for PAI of periodontal disease and pocket.	Tunable 680-970 nm OPO laser. At 5-7 ns, the fiber bundle emits 22 mJ/pulse. Hockey stick transducer as a detector.	Periodontal pocket depth was created artificially using swine jaws (ex-vivo.	Based on the photoacoustic image, the second molar pocket is deeper than the first premolar, the premolar pocket depth was 1.2 mm and the second molar was 5 mm.	Suggesting the development of a more portable high-frequency transducer with a particular oral imaging design to encompass human tooth.
Mozaffarzadeh et al. (2021)	Human periodontal structure and pocket depths as imaged by PA-US.	Nd:YAG laser (680–970 nm, 4–6 ns. Linear array transducer as a detector.	Healthy female subject for PA-US periodontium imaging (in-vivo).	The pocket depth identified in a healthy subject based on the PA image can be imaged accurately.	This study can be improved to reduce operator skill burden and patient discomfort in clinical practice by examining periodontal pocket depth with PA-US imaging.
Sari et al. (2022)	PAI for periodontal disease examination.	Diode laser of 532 nm 200 mW. Condenser microphone as a detector.	The periodontal tissue from rats (ex-vivo).	Periodontitis tissue generates a higher acoustic intensity than healthy periodontal tissue.	Periodontal disease can be identified using the PAI system. The straightforward PAI should be improved upon to create a PAT.
Fu et al. (2022)	Described a transducer for imaging the posterior teeth, including periodontal pocket evaluation, using PA-US.	A diode laser (808 nm, 1 kHz, 0.7 mJ/cm^{2,} 100 ns). Ultrasound transducer as a detector.	Posterior teeth and periodontal pocket from healthyhuman and periodontal disease human (in-vivo) .	The transducer was able to image the periodontal tissue of molar teeth in the posterior area.	The transducer can fit at the posterior region to scan the molars according to the innovative tooth-brush design. To cut expenses, the excitation source uses a laser diode.
Fu et al. (2022)	To create a technique for photoacoustic imaging to image the periodontal pocket.	A laser (680-970 nm). The hockey stick transducer as a detector.	A healthy human with adequate dental hygiene, incisors and premolars that extracted (in-vivo).	The hockey-stick transducer's distinctive angle design enables it to image molars than conventional transducers. The results indicate that the pocket depths produce higher intensity that are comparable to those of a healthy human.	The hockey-stick transducer's distinctive angle form enables it to image posterior teeth than conventional transducers. Due to the enormous size of the instrument, the last two molars of human patients cannot be imaged in photoacoustic mode. To examine every tooth in oral cavity, a more portable high-frequency transducer that is made especially for oral imaging was

(*continued on next page*)

Table 1 *(continued)*

Authors (Year)	Study Purpose	Laser Settings and Methods	Objects/Samples	Outcome	Comparison
					required.
Moore et al. (2022)	An imaging probe with dual modes for fluorescent and photoacoustic to identify *Porphyromonas gingivalis* infection.	680 nm Q-switched Nd:YAG laser. Fluorescent and PAI transducer as the detectors.	Samples of gingival taken from 14 and 6 human, respectively, with and without periodontal disease (in-vivo).	The most severe diseased subjects had the strongest acoustic signal.	In-vivo P. gingivalis infection can be imaged using a dual mode transducer. This system has some limitations due to the low signal-to-noise ratio in blood, which affects many small-molecule photoacoustic probes.
Tasmara et al. (2023)	PAI to detect hidden caries.	Diode laser with 532 nm 200 mW and condenser microphone as a detector.	The human extracted teeth (ex-vivo).	The PA signal of healthy teeth was −74.2 ± 0.1 dB, while it was −81.2 ± 0.5 dB for teeth with hidden caries.	Because this study is an ex-vivo investigation, further studies are necessary to compare PAI with other methods for detection of hidden tooth decay.

Arabpou et al., 2019; Cheng et al., 2016; Dias et al., 2018; El-Sharkawy and El Sherif, 2012; Khosroshahi and Valizadeh, 2020; Koyama et al., 2018; Lee et al., 2017; Li and Dewhurst, 2016; Periyasamy et al., 2018; Rao et al., 2011; Sampathkumar et al., 2014; Silva et al., 2021; Yamada et al., 2016), animal model for mimicking periodontal diseases (Sari et al., 2022), and oral soft tissues from rats (Widyaningrum et al., 2018, 2020). PAI was also discovered to be useful in the investigation of dental implants and oral biofilms (Dias et al., 2018; Lee et al., 2017). Fig. 3 provides a summary of PAI studies in this review based on the investigated object. Since PAI systems vary between studies, Table 2 presents a list of PAI systems utilized in the field of dentistry research.

4. Discussion

4.1. Laser in dentistry

The first laser device was developed in 1960 based on Einstein's early 1900 investigations. Since then, numerous medical and surgical procedures have utilized lasers (El-sharkawy et al., 2006). Upon coming into contact with a tissue, the laser is reflected, scattered, absorbed, or transferred to nearby tissues. Given that proteins, water molecules, pigments, and other molecules found in biological tissues are responsible for optical absorption, the absorption coefficient is wavelength dependent (Newman et al., 2019).

In 1964, Goldman et al. and Stern and Sognnaes performed the initial studies on dentition using laser as a surgery technique. Both study used a ruby laser (694 μm), but this laser had heated consequences that stimulated cracking teeth and irreparable damage to nerve fibers (Niemz, 2007). Owing to the significant advances in their clinical applications, lasers are set a new standard in dentistry. Lasers may be used to examine hard and soft tissues without the need for direct contact, vibrations, or discomfort, making them applicable in a wide variety of dental specialties (Ranjana et al., 2021).

The utilization of laser for periodontal treatment is supported by the fact that the periodontium is composed of hard and soft tissues. Among several lasers available, high-power

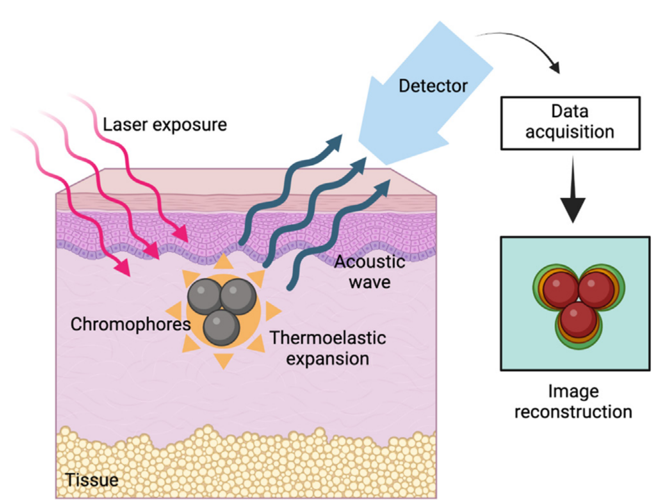

Fig. 2 Photoacoustic imaging process.

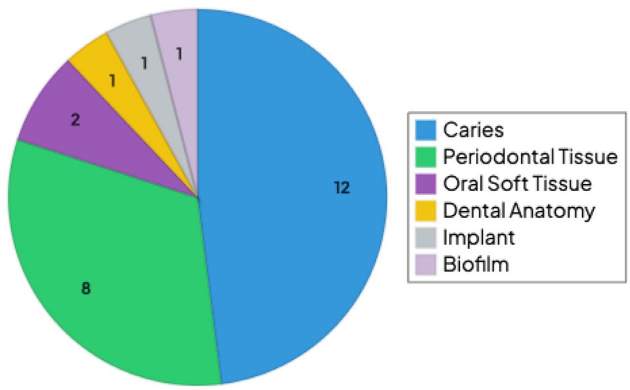

Fig. 3 Number of PAI studies in dentistry classified in terms of the investigated object.

lasers such as a diode, CO_2, and Nd:YAG lasers for surgical purposes are generally employed in periodontics. Owing to their superior soft tissue ablation properties, these lasers have been accepted for use in periodontal and oral surgical treatment for soft tissue management (Freire et al., 2020; Grzech-leśniak et al., 2018; Hanna et al., 2022; Mobadder et al., 2022; Sadiq et al., 2022; Zhao et al., 2020). Gingivectomy, frenectomy, and comparable soft tissue treatments, including the elimination of melanin pigmentation, are all procedures that can be performed using these lasers (Agha and Polenik, 2020; Lazar et al., 2022; Lione et al., 2019; Uraz et al., 2018). The use of lasers in dentistry has also been investigated for other indications, including subgingival debridement and curettage, granulation tissue removal during flap surgery, osseous recontouring, implant surgery, implant maintenance, *peri*-implantitis management, and laser surgery (Ghinassi et al., 2020; Giacomo et al., 2016; Li et al., 2020; Simões et al., 2021; Sumra et al., 2018).

4.2. Photoacoustic imaging

In PAI, a laser is used as an excitation source. PAI is an innovative non-invasive biomedical imaging that utilize optical absorption contrast to detect spectroscopic fingerprints of various tissues with deep imaging levels and great spatial detail. The detection of light-induced ultrasonic (US) waves is the basis of this hybrid imaging method. Certain exogenous contrast agents or endogenous tissue chromophores can absorb nanosecond pulsed or time-modulated light and transform optical energy into localized temperature rises that can be converted to ultrasonic or acoustic waves. Acoustic detectors are commonly used in PAI systems to record acoustic or ultrasonic waves produced by laser-exposed objects. The chromophores in the investigated object is mapped by the photoacoustic image and then reconstructed as a photoacoustic image from the acoustic signal obtained from the detector (Burgholzer et al., 2020; Zhao et al., 2019) (Fig. 2).

The laser-induced photoacoustic effect was initially used in dentistry to detect dental caries (El-sharkawy et al., 2006); a Q-switched Nd:YAG laser (1064 nm) was used to produce a measurable reaction in the teeth. A piezoelectric transducer and a Michelson interferometer were employed as detectors, both of which responded identically to the carious and healthy teeth. Meanwhile, the acoustic signal of carious teeth had a higher prevalence than normal teeth (El-sharkawy et al., 2006). PAI has been investigated to detect tooth decay and hidden caries (Tasmara et al., 2023). To date, PAI has not been widely adopted in dentistry. Therefore, further studies are necessary to develop this imaging technique in dentistry.

Table 2 Designs of PAI system in dentistry.

System	Number of Study	Advantages	Application in dental practice
Photoacoustic Ultrasound (PA/US) (Fu, Khazaeinezhad, et al., 2022; Fu, Ling, et al., 2022; Fu et al., 2021; Lin et al., 2017; Moore et al., 2018, 2022; Mozaffarzadeh et al., 2021)	7	High resolution, non-invasive	Not yet available and has been investigated on human subject
Photoacoustic Microscopy (Alifkalaila et al., 2021; Rao et al., 2011; Sari et al., 2022; Silva et al., 2021; Tasmara et al., 2023; Widyaningrum et al., 2018, 2020)	7	Low cost, non-invasive	Not yet available
Photoacoustic Tomography (PAT) (Arabpou et al., 2019; Cheng et al., 2016; Li and Dewhurst, 2016; Yamada et al., 2016)	4	High resolution, non-invasive	Not yet available
Surface Acoustic Wave technique (El-Sharkawy and El Sherif, 2012)	1	Non-invasive	Not yet available
All-Optical Photoacoustic Imaging (Sampathkumar et al., 2014)	1	Non-invasive	Not yet available
Acoustic-Resolution Photoacoustic Microscopy (AR-PAM and PA/US (Lee et al., 2017)	1	Low cost, high resolution, non-invasive	Not yet available
Photoacoustic Spectroscopy (PAS) (Dias et al., 2018)	1	Non-invasive	Not yet available
Optical-fiber based PAI system (Koyama et al., 2018)	1	High resolution, non-invasive	Not yet available
AR-PAM and PAT (Periyasamy et al., 2018)	1	High resolution, low cost, non-invasive	Not yet available
Photoacoustic sensor and laser-induced plasma spectroscopy (Khosroshahi and Valizadeh, 2020)	1	Non-invasive	Not yet available

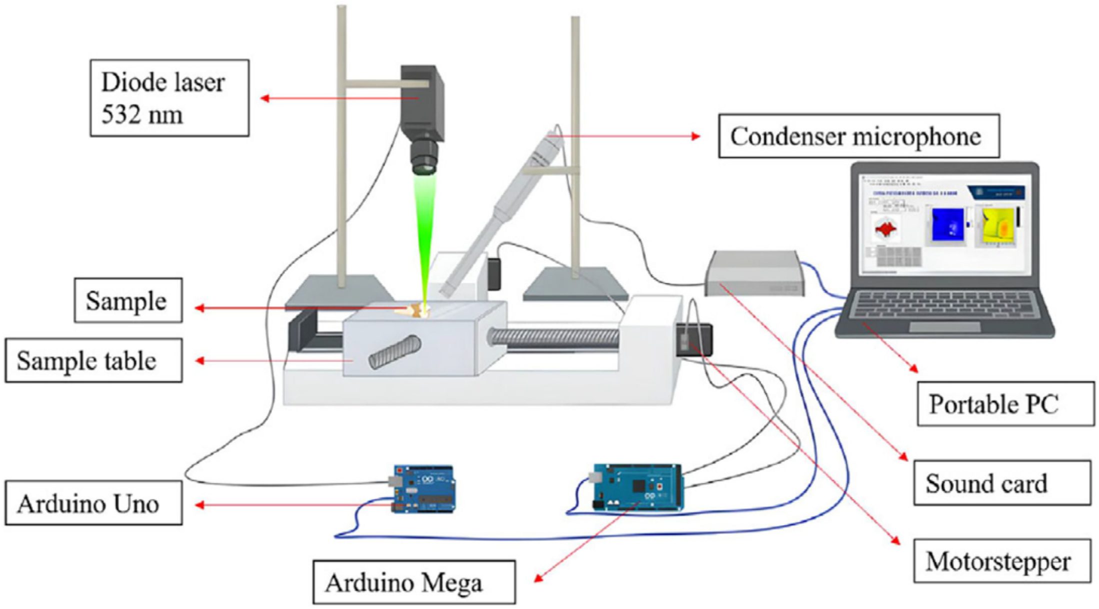

Fig. 4 A simple photoacoustic microscopy system that combine diode laser, microphone and custom-build X-Y stage for ex vivo imaging. Figure from Tasmara et al., 2023 is used with permission.

4.3. Compilation of study results and critical appraisal

Table 1 summarizes the PAI investigations in dentistry throughout the last decade. Fig. 3 also includes a summary of the review based on the object investigated with PAI. According to the data in Fig. 3, there have been 25 photoacoustic imaging studies in dentistry over the last decade with various objects such as caries, periodontal tissue, oral soft tissue, dental anatomy, implant, and biofilm. Referring to Tables 1 and Fig. 3, the majority of research on PAI in dentistry is still focused on its potential use for caries diagnosis. Nowadays, technologies for caries detection are highly advanced and have been employed in clinical settings. Dentists generally utilize intraoral radiography to identify and diagnose dental caries. Lasers, specifically fiber-optic transillumination and near-infrared light transillumination, have been recently introduced for non-ionizing caries detection (Antipoviene et al., 2020; Litzenburger et al., 2020; Marmaneu-menero et al., 2020; Strassler and Pitel, 2016). Since PAI employs laser or other non-ionizing radiation sources, it has the potential to be advanced as an alternative imaging modality for the detection of oral diseases, including caries. However, the fact that PAI has not been applied for caries detection in dental practice represents a challenge for future research.

Several PAI systems have been developed over the last decade and are being employed in various studies. Table 2 shows the various designs in PAI. The PAI system utilized in dentistry is available in a range of configurations, including PAM (Alifkalaila et al., 2021; Rao et al., 2011; Sari et al., 2022; Silva et al., 2021; Tasmara et al., 2023; Widyaningrum et al., 2018, 2020), PAT (Arabpou et al., 2019; Cheng et al., 2016; Li and Dewhurst, 2016; Yamada et al., 2016), photoacoustic ultrasound (PA/US) (Fu, Khazaeinezhad, et al., 2022; Fu, Ling, et al., 2022; Fu et al., 2021; Lin et al., 2017; Moore et al., 2018, 2022; Mozaffarzadeh et al., 2021), SAW technique (El-Sharkawy and El Sherif, 2012), all-optical PAI (AOPAI) (Sampathkumar et al., 2014), acoustic-resolution PAM (AR-PAM) and PA/US (Lee et al., 2017), photoacoustic spectroscopy (Dias et al., 2018), AR-PAM and PAT (Periyasamy et al., 2018), optical-fiber based PAI system (Koyama et al., 2018), photoacoustic sensors and laser-induced plasma spectroscopy (Khosroshahi and Valizadeh, 2020). PAM is most frequently used to examine oral soft tissues, characterize dental anatomy, and detect dental caries; and AR-PAM with PA/US is applied to image dental implant, jawbone, and teeth in the jawbone. In addition to PAM, PA/US is frequently utilized to image the depth of periodontal pockets (Alifkalaila et al., 2021; Lee et al., 2017; Rao et al., 2011; Silva et al., 2021).

Fig. 4 shows how the PAM system operates. A laser diode (532 nm, 200mW) was employed as the light source. The condenser microphone received the photoacoustic signal, which the sound card then sent to the computer. A stepper motor was used to move a sample along the XY axis after it had been set up on the sample table (Tasmara et al., 2023).

The teeth have multiple layers identified as dental structure and include the enamel, dentin, cementum, and pulp (Newman et al., 2019). PAI for the characterization of dental anatomy revealed that each tooth layer generates a distinct acoustic signal. Pulp, dentin, and enamel generate the highest, middle, and lowest acoustic signals, respectively (Alifkalaila et al., 2021). The coefficients of heat transfer and absorption tend to be significantly higher in pulp tissues than in hard tooth tissues (Alifkalaila et al., 2021; Yamada et al., 2016). Dentin and pulp exhibit more signal attenuation than enamel because the former have more than 50% biological material and fluids that scatter and absorb radiation more effectively than the latter. Therefore, the quantity of energy absorbed by the tissues determines the acoustic intensity (Alifkalaila et al., 2021). Differences in PA signal are observed between carious and healthy teeth. The thermoelastic expansion in carious teeth is hypothesized to be larger than that in healthy teeth, and the acoustic signal produced by decaying teeth is higher than that produced by healthy teeth (Arabpou et al., 2019; El-Sharkawy and El Sherif, 2012; Khosroshahi and Valizadeh, 2020; Koyama et al., 2018; Li and Dewhurst, 2016; Periyasamy et al., 2018; Rao et al., 2011; Sampathkumar et al., 2014; Silva et al., 2021).

PAI can evaluate the pocket depth in periodontal tissues and therefore shows potential in the non-invasive monitoring of periodontitis (Fu, Khazaeinezhad, et al., 2022; Fu, Ling, et al., 2022; Fu et al., 2021; Lin et al., 2017; Moore et al., 2018, 2022; Mozaffarzadeh et al., 2021). When the acoustic signal of inflamed periodontal tissue is higher than that of healthy periodontal tissue, PAI can be utilized to distinguish between the two types of periodontal tissue. Photoacoustic image demonstrates the differences with the color red predominates in the high acoustic signal (Sari et al., 2022). Meanwhile, a PAI study on a tooth implant fixed in a porcine jawbone revealed that PA signal of the teeth in the abutment area enhanced with the laser intensity. The abutment, fixture borders were hazy, and the detected PA signal strength dropped at a depth of 20 mm, but the implant's PA signal was discernible beneath a 20-mm layer of chicken breast tissues that mimicking oral tissue surrounding the dental implant (Lee et al., 2017).

Several chromophores in biological tissues absorb laser energy and then generate a detectable photoacoustic effect (Li et al., 2021). Hemoglobin is a chromophore found in a variety of tissues, including the pulp of the tooth's inner layer. Vital pulp generates a stronger acoustic signal than enamel or dentin due to the presence of hemoglobin in the pulp's blood vessels. However, the acoustic signal of nonvital pulps is higher than that of enamel or dentin. This phenomenon is related to the presence of cavities in the pulp that provide it with mechanical capabilities different from those of the hard tissues (enamel, dentin or cementum) of the teeth (Alifkalaila et al., 2021; Rao et al., 2011; Yamada et al., 2016).

According to Table 1, the PAI experiments were also conducted to investigate the potential of this technique for imaging teeth, oral soft tissue, implants, and biofilms (Dias et al., 2018; Lee et al., 2017; Widyaningrum et al., 2018, 2020). PAI hasn't been developed for use in clinical settings because there haven't been many PAI studies on human subject. As a result, improvements based on the data obtained are required to establish PAI as an imaging technique for screening and diagnosing disorders that manifest in the oral soft tissues. PAI utilizes a laser as an excitation source with limited penetrating depth in oral tissues depending on its wavelength and intensity (Ash et al., 2017; Setiawan et al., 2019). This condition may limit the laser's capacity to penetrate the tooth's hard tissues. The chromophores in oral soft tissues are more variable than those in hard tooth tissues, allowing for the simple detection of pathological changes in oral soft tissues using PAI. Early detection is fundamental for certain oral disorders, including oral cancer and tumors, periodontitis, non-odontogenic and odontogenic inflammation induced by cariogenic bacterial infections, and tooth decay (dental caries).

PAI also shows potential usage for extra-oral imaging to examine disorders affecting the head and neck region. The applicability of PAI detector will increase when it is integrated with an excitation source, which will simplify the clinical application for clinicians and enhance patient convenience. For intraoral examination, the size of the detector should be adjusted for use in the oral cavity. For extra-oral inspections, size of transducer must be changed, ranging from compact to large sizes for examinations on broad areas, to meet the demands of clinical examination and diagnostic purposes.

Studies of PAI for biofilm detection are currently limited, and only one has been conducted on oral biofilms in the recent decade (Dias et al., 2018). A biofilm known as oral plaque grows on the tooth structures. Research on oral biofilms generally focuses on their role as an etiological agent of two major illnesses affecting tooth decay and periodontitis. Application of scientific information on oral biofilms in developing practical activities for identification and prevention of oral disease has led to the evaluation of methodologies for the quantification of dental plaque (Dias et al., 2018). The photoacoustic absorption spectrum is a representation of the acoustic signals created by the dental enamels with and without a biofilm (Dias et al., 2018).

Tables 1 and 2 indicate the advantages and disadvantages of PAI systems developed in several studies from this review. In general, low cost, high resolution, high contrast, and non-invasiveness are the highlights of PAI systems. The system's weakness, however, is that the transducer is still large, making it difficult to get to the inside of the oral cavity. Thus, a smaller transducer is required for intraoral examination. The majority of radiation sources on PAI studies in dentistry still utilize bulky lasers like Nd:YAG. Consequently, the PAI system will cost less if more rugged light sources like LEDs and pulsed laser diodes are used as the radiation source. 532 nm and 1064 nm are the laser wavelengths used to detect hard tissue, such as caries, lesions, and dental anatomy. The laser used to detect oral soft tissue has a wavelength between 680 and 970 nm. Based on the outcomes of the review, it can be indicated that the PAI system can be utilized as a diagnostic tool since it can distinguish between soft and hard tissues in the mouth, as well as detecting tooth and oral diseases. The advancement of PAI enables this imaging technique to be developed as an alternative diagnostic tool while also complementing the current imaging modality in dental practice.

PAI is currently used in medical diagnosis, such as stroke monitoring (Yang et al., 2021), tumor detection (Alchera et al., 2022), cancer (Shi et al., 2022), and carcinoma diagnosis (Stridh et al., 2022). In comparison to the advancement of PAI research in dentistry, PAI technology has not been widely used to diagnose oral disease. Therefore, further clinical and or experimental studies are needed in those fields. PAI research for applications in dentistry must be accelerated to reach the community's needs for dental and oral health systems. In order to realize a low-cost, non-invasive photoacoustic imaging system.

5. Conclusion

Future studies must emphasize the wide application of PAI in various clinical examinations in dentistry, not only for the identification of tooth decay but also for soft tissue disorders, head and neck diseases, and the evaluation of dental implants, other oral diseases, and oral biofilms. For clinical applications, the PAI design must be customized to accommodate the examination of the area under investigation.

A number of studies have demonstrated that PAI has the potential to detect caries, allowing it to be developed as an alternative to x-ray imaging, which has previously been used in dental practice. PAI utilizes a laser imaging source with non-ionizing exposure, making it biologically safer than x-ray. Furthermore, PAI has the potential to image chromophores found in oral soft tissue that x-ray imaging cannot be utilized for it. LEDs or pulsed diode lasers can be used as radiation sources in PAI systems to reduce costs. Additionally, the transducer should be minimized to fit inside the mouth.

This review concluded that PAI has widespread application in dentistry. During the last decade, this technique has been investigated for the identification of tooth decay, the examination of periodontal tissues, oral soft tissues, implants, and the investigation of oral biofilms. However, the majority of PAI research is still conducted in ex-vivo phase. Dental healthcare professionals anticipate that advances in PAI research will lead to the development of alternative non-ionizing imaging technologies that are comfortable for patients, simple to use, and capable of providing accurate information at an affordable cost. Multidisciplinary collaboration involving scientists, engineers, and dentists is required to achieve this goal.

CRediT authorship contribution statement

Atika Windra Sari: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Rini Widyaningrum:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Andreas Setiawan:** Writing – review & editing, Validation. **Mitrayana:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors acknowledge the Indonesian Endowment Fund for Education (*Lembaga Pengelola Dana Pendidikan*) for providing support for this review.

Ethical statement

No ethical issues were raised during the study presentation.

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