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Perspective: Principles and specifications of photothermal imaging methodologies and their applications to non-invasive biomedical and non-destructive materials imaging

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(Received 15 June 2018; accepted 13 October 2018; published online 29 October 2018)

This article discusses a number of dynamic thermography techniques used for analysis of captured raw infrared images of objects. The most widely used, as well as state-of-the-art, modalities are outlined in terms of their operating principles and their specifications. Special attention is paid to truncated correlation photothermal coherence tomography, a novel method that provides high contrast and high resolution 3D images of objects. Applications of thermography in medical imaging, art analysis, and non-destructive imaging of industrial materials are discussed. Published by AIP Publishing. https://doi.org/10.1063/1.5044748

I. INTRODUCTION

Thermography is a technique whereby the condition of objects is studied by means of precisely monitoring temperature variations over the surface of such objects. In the past few decades, there has been increased interest in active infrared thermography for non-destructive imaging (NDI) of industrial materials and art objects and medical diagnosis applications. Industrially, thermography is used in military, aerospace, power generation, and automotive industry applications to detect both manufacturing and in-service environment-induced defects.1–8 Recently, research was undertaken to apply thermal imaging in the field of art conservation to examine structures of panel paintings, marqueteries, and other art objects for diagnostics and authentication purposes.9–12 Thermography is a non-contact, non-ionizing, fast, and reliable technique and is receiving growing attention in the medical field. This technique is utilized in the detection of early caries in teeth with better sensitivity than radiography13–16 and bone imaging with the aim of establishing a diagnostic technique for osteoporosis.17,18 In breast thermal imaging, an abnormal infrared image has been proven to be an effective marker for a high risk of developing breast cancer.19–22

Dynamic thermography based on several signal processing methods has been proposed to improve the performance of photothermal systems being either in the time domain or in the frequency domain. For the time-domain techniques, the resulting amplitude images are very prone to local optical and infrared surface features such as non-uniform heating, emissivity variation, ambient reflections, and sample surface conditions.23 However, frequency domain techniques give rise to phase images and carry more information about the sample. Phase images are emissivity normalized and thus superior to amplitude images in terms of depth probing capability as they probe deeper than amplitude.23–26 Lock-in thermography (LIT), a well-known infrared imaging modality, determines the amplitude and phase of the sample temperature oscillations (“thermal waves”).27 Since LIT rejects noise signals at frequencies other than the reference frequency, it provides high signal-to-noise ratio (SNR) thermal wave images. In 1996, lock-in reconstruction algorithms combined with pulsed photothermal radiometry (PPTR)28–31 provided faster and higher penetration depth and resolution thermal images than conventional dc infrared thermography. In this technique, phasograms (phase maps) are of particular interest, and for this reason the modality is called pulsed phase thermography (PPT).32

Many attempts have been made to localize energy in the thermal-wave field and to overcome the axial resolution limitations imposed by the parabolic diffusion waves. Thermal waves are governed by the parabolic heat diffusion equation and therefore lack wave fronts causing depth-integrated (rather than localized) energy distribution. The diffuse nature of heat conduction in a medium results in poor axial resolution, which degrades with time and distance from the source. Historically, the first signal processing method proposed in the heat conduction field to improve the axial resolution was pseudorandom binary sequence (PRBS) optical excitation followed by match-filtering.33 Later on, frequency modulated photothermal wave spectroscopy was proven to provide accurate determination of the system impulse response function, superior dynamic range properties, and a faster response compared to PRBS excitation.34–36 More recently, the concept of cross-correlation match-filtering was used for localizing energy of the received signal under a single peak located at a delay time τp equal to the delay time between transmitted and received signals.37,38 More energy localization was achieved by incorporating a pulse compression methodology which reduces the cross-correlation width while increasing its peak height. Linear frequency modulation (LFM) excitation (wide-band frequency modulation)38 or

124, 160903-1 Published by AIP Publishing.
Binary Phase Coded (BPC) modulation (narrow-band phase encoding) are two kinds of pulse compression techniques. Incorporation of the cross-correlation technique with LFM excitation and with BPC beam modulation introduced the concept of thermal wave radar (TWR) and thermal coherence tomography (TCT), respectively. Subsequently, chirp pulsed excitation signals (with constant pulse-width) were combined with the TWR reconstruction algorithm and exhibited SNR improvement up to two orders of magnitude compared to three distinct chirped excitation waveforms (sine-wave, square-wave, and constant duty cycle pulses) under equal exposure energy of lower than 100 mJ.17

Recently, truncated correlation photothermal coherence tomography (TC-PCT) was introduced and later enhanced, thus becoming the only dynamic thermal imaging method that provides a highly axially resolved 3D image of a specimen. Apart from chirped pulse excitation with fixed pulse width and pulse-compression, TC-PCT uses a time-evolving filter to reconstruct the depth distribution of photothermal parameters and provides 2D and 3D images of a sample as the photothermal analog of optical coherence tomography (OCT).

Among the main kinds of frequency domain active thermography are lock-in thermography (LIT), pulse phase thermography (PPT), thermal wave radar (TWR), binary phase coding thermal coherence tomography (BPC-TCT), chirp pulse photothermal radar (CPPTR), and truncated correlation photothermal coherence tomography (TC-PCT). Here, we review these data analysis methodologies and their applications, specifications, advantages, and disadvantages.

II. THERMAL IMAGING INSTRUMENTATION AND SIGNAL GENERATION

A generic active thermography instrumentation scheme includes a light source (a broadband lamp, flash controls, heat gun, or a diode laser followed by a beam homogenizer), a single detector or an IR camera (usually in the spectral range of 1–5 μm) that measures surface temperature, signal generator triggered by a computer, data acquisition system, and a computer to synchronize the systems and to perform signal processing on the raw infrared images (Fig. 1). Both transmission and backscattering modes can be employed to perform thermography, but the backscattering mode is more attractive as it is not always possible to have access to the other side of the object. The procedure to perform thermography can be divided into 4 steps depicted in Fig. 1. First, the specimen’s surface is heated with a thermal source (e.g., using photographic flashes in PPT or using a laser as a photothermal heat source in TC-PCT. All reported images in this report were generated with 808 nm diode laser excitation). A heating controller (e.g., laser driver) is usually needed to drive the heating source and to modulate the beam. The controller is connected to a signal generator to receive the modulating signal. Second, the thermal signal continues to diffuse through the material bulk following the heat deposition cutoff at the surface. Third, the surface temperature conductive change is monitored using an infrared camera. A thermal map of the surface is recorded at constant time intervals creating a video of the temperature evolution. Finally, in the fourth step, the thermogram sequence is processed with the reconstruction algorithm on a computer. Sometimes, a data acquisition system is needed to record the modulating optical signal that heats the sample surface for post-processing algorithms. Studying different reconstruction algorithms is the focus of this paper.

In photothermal imaging techniques, the illumination schemes can be either continuous wave (CW) or pulsed excitation. In the CW method, the excitation signal is in the form of a low-power, continuous, amplitude/frequency modulated pattern. The sample thermal response to harmonic stimulation is described by an oscillating thermal wave. In the pulsed thermography (PT) method, however, a few-millisecond high-power optical pulse impinges on a material and the following temperature decay are recorded. An ideal Dirac pulse (t) in the time domain has an infinite flat spectrum in the frequency domain. When a specimen is pulse heated, a rectangular pulse instead of the ideal Dirac pulse is used; thus, thermal waves of many frequencies with various amplitudes instead of a constant amplitude are simultaneously launched into the sample. For a rectangular pulse of width τ and amplitude A centered at t = 0, the frequency content is expressed by the well-known sinc waveform, Arsin(ωτ)/ωτ, where ω is the angular frequency. Therefore, unlike CW, PT generates a broad spectrum of frequencies in a specimen.

Depending on the incident radiation, an oscillatory or a transient thermal wave is generated in the sample. Analytically, photothermal heat diffusion models can be developed in a sample by solving a heat conduction boundary value problem. To date, solutions to the heat diffusion problem for different excitation signals and a wide range of geometries and materials have been derived. In all the solutions, thermal diffusion length \( L = \sqrt{2\alpha/\nu} \) and heat transfer rate \( (\nu = \sqrt{2\alpha/\omega}) \) play key roles as they indicate penetration depth and propagation speed in a sample with a thermal diffusivity \( \alpha \), at a specific modulation frequency \( f = \frac{\omega}{2\pi} \). Thermal diffusion length is inversely proportional to

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**FIG. 1.** Active thermography system.
the square root of modulation frequency, while propagation speed is proportional to the square root of frequency. These facts indicate that high frequency thermal waves limit their diffusion close to the surface, while low frequency heat waves dissipate to a deeper region, but slowly.

III. DATA ANALYSIS METHODOLOGIES

A. Lock in thermography (LIT)

LIT has been applied to infrared data to enhance the SNR of thermal images. Typically, a sample is excited at a fixed frequency and the LIT method records the demodulated output signal at this reference frequency. Suppose the excitation signal is a sine wave at angular frequency \( \omega \) with a large heating beam radius to satisfy one dimensional heat flow. When the heating source is localized on the surface of an object as a result of light absorption, the conductive heat flow inside the material is given by Eq. (1).

\[
S(z, t) = A(z) \cos(\omega t - \varphi(z))
= T_0 e^{-z/\mu} \cos\left(\omega t - \frac{z}{\mu} - \varphi_1\right).
\]

The thermal-wave response recorded by a single detector or a camera will be proportional to \( S(0, t) = T_0 e^{\omega t/\mu} \cos(\omega t - \varphi_1) \) where \( T_0 \) is the initial change in the temperature (signal amplitude), \( \omega \) is the modulation angular frequency, \( \mu \) is the thermal diffusion length, and \( \varphi(z) \) and \( \varphi_1 \) are the phases at depth \( z \) and the initial phase, respectively. The lock-in technique multiplies the response signal by the reference signal, \( T_R e^{i \omega t + \varphi_R} \), and filters the output with a low pass filter.

\[
S_{n1} = T_0 e^{\omega t/\mu} \cos(\omega t - \varphi_1) \times T_R e^{i \omega t + \varphi_R}
= \frac{1}{2} T_0 T_R \cos(\varphi_R - \varphi_1) + \frac{1}{2} T_0 T_R \cos(2 \omega t R - \varphi_R - \varphi_1). \tag{2}
\]

The filtered output is proportional to the cosine of the phase difference between the input and the reference signals. To measure the thermal-wave amplitude and phase, the reference signal 90° out of phase is also multiplied with the response signal [Eq. (4)] and low pass filtered [Eq. (5)]. Then, amplitude and phase are measured by Eqs. (6) and (7), respectively.

\[
S_{n2} = T_0 e^{\omega t/\mu} \cos(\omega t - \varphi_1) \times T_R e^{i \omega t + \varphi_R \pi/2}
= \frac{1}{2} T_0 T_R \cos\left(\varphi_R - \varphi_1 + \frac{\pi}{2}\right)
+ \frac{1}{2} T_0 T_R \cos(2 \omega t R - \varphi_R - \varphi_1 - \frac{\pi}{2}), \tag{4}
\]

\[
S_{n2 \text{--filtered}} = \frac{1}{2} T_0 T_R \cos\left(\varphi_R - \varphi_1 + \frac{\pi}{2}\right)
= \frac{1}{2} T_0 T_R \sin(\varphi_R - \varphi_1). \tag{5}
\]

Demodulated amplitude:
\[
A = \frac{2}{T_R} \sqrt{\left(S_{n1 \text{--filtered}}\right)^2 + \left(S_{n2 \text{--filtered}}\right)^2}, \tag{6}
\]

Demodulated phase:
\[
\varphi = \tan^{-1}\left(S_{n2 \text{--filtered}}/S_{n1 \text{--filtered}}\right). \tag{7}
\]

To probe deeper, a low-frequency excitation signal needs to be applied leading to a longer acquisition time to obtain a proper number of periods, since increasing the number of periods aids in reducing the noise level and improves image quality. Besides the required longer acquisition time, low frequency thermal waves lack the desired resolution. Therefore, one needs to consider a compromise between maximum detection depth and depth resolution.

Since LIT performs at a single frequency, the detector captures information from a single diffusion length. To reconstruct a 3D image of the sample, the imaging should be repeated at different frequencies, and the computation should be performed for each scanned frequency, which is time consuming, and the result has a poor axial resolution.

B. Pulsed phase thermography (PPT)

More than 20 years ago, pulsed phase thermography (PPT) was introduced which combines pulse heating and lock in thermography and uses the merits of both approaches. PPT provides better defect shape resolution than LIT, with the advantage that several frequencies are available with a single experiment. In PPT, a specimen surface is illuminated by a pulse, and the temperature evolution on the inspected surface is monitored by an IR camera recording a thermal map (thermogram) of the surface at regular time intervals \( \Delta t \) and creating a 3D matrix of \( N_x \times N_y \times N_t \), where \( N_x \) and \( N_y \) are dimensions of a single thermographic frame in pixels and \( N_t \) is the number of frames collected [Fig. 2(a)]. One recorded thermal transient of a pixel is displayed in Fig. 2(b).

PPT extracts various frequencies of a generated thermal transient followed by an excitation pulse and links it to different depths in the specimen. In the PPT technique, a one-dimensional discrete Fourier transform (DFT) is used to extract different frequencies. The DFT on each pixel of the thermogram sequence can be written as follows:

\[
F_n = \Delta t \sum_{k=0}^{N-1} T(k\Delta t)e^{-2\pi i kn/N} = R_n + iM_n, \tag{8}
\]

where \( T(k\Delta t) \) is the sampled temporal evolution of each pixel in the field of view extracted from the image sequence, \( i \) is the imaginary unit, \( R_n \) and \( M_n \) are, respectively, the real and imaginary parts of the transform, subscript \( n \) designates the frequency increment \( (n = 0, 1, \ldots, N) \), and \( N \) is the total number of frames in the sequence. After computing \( R_n \) and \( M_n \), the amplitude \( (A_n) \) and phase \( (\varphi_n) \) are measured with the
following formulas:

\[ A_n = \sqrt{\left( Re_n^2 + Im_n^2 \right)} \quad \text{and} \quad \varphi_n = \tan^{-1}\left( \frac{Im_n}{Re_n} \right). \quad (9) \]

The 3D matrix of recorded thermal signals is transformed to a 3D matrix in the frequency domain, and contrast (amplitude) profile and phase profile are measured from Eq. (9) [Figs. 2(c) and 2(d)].

Drawbacks of PPT are considerable noise content in phase data which increases with frequency\(^53\) and limitation in quantitative analysis of the data. Therefore, different algorithms such as synthetic data\(^{51}\) and the wavelet transform\(^{54}\) are applied to the thermal signals for de-noising the phasograms and retrieving quantitative information from PPT results, respectively.

C. Thermal wave radar (TWR)

Despite the promising results of LIT, this modality cannot probe deeply into the sample as a result of reduced depth penetration of high-frequency thermal waves and reduced resolution of low-frequency thermal waves. Additionally, single frequency thermal waves yield depth integrated information from approximately a single diffusion length. Later, multi-frequency modalities were developed by Tabatabaei and Mandelis\(^38\) and Mulaveesala \textit{et al.}\(^37,55\) as alternative solutions to this problem. The TWR uses a linear frequency modulation (LFM) pulse compression technique and cross-correlation signal processing.\(^34-36\) In an LFM chirp as expressed in Eq. (10a), the instantaneous frequency changes linearly with time.

\[ A(t) = A_0 \sin[2\pi f(t)t], \quad (10a) \]

\[ f(t) = f_0 + kt, \quad (10b) \]

\[ k = \frac{(f_e - f_0)}{2T}, \quad (10c) \]

where \( A_0, f_0, f_e, k, \) and \( T \) are the modulated waveform intensity, frequency modulation function, starting frequency, ending frequency, chirp sweep rate, and chirp time, respectively. This excitation waveform results in chirped thermal...
waves from the sample, yet embedded in noise. In the radar sciences, a matching-filtering technique has been used to enhance range resolution and to improve SNR by detecting a pre-known signal within highly noised channels. The TWR method computes the cross-correlation between a reference waveform derived from the excitation waveform, \( R(\tau) \), and the resulting photothermal signal, \( S(t + \tau) \), measured at the delay time \( t \), using the following equation:

\[
C_R(t) = \int_{-\infty}^{\infty} R^*(\tau)S(t + \tau) d\tau.
\]  

(11)

Here \( R^*(\tau) \) is the complex conjugate of the reference signal. Since the heat conduction process takes longer than the radiative (emissive) process to reach the surface, multiple sources at different depths can be detected as a result of cross-correlation with the reference pulse. The output of this cross-correlation contains a delayed peak, the delay being a function of thermophysical properties and the depth of sources below the specimen’s surface. For example, for a steel sample with different subsurface hole thicknesses [Fig. 3(a)] the location of the TWR cross-correlation peak shifts toward shorter delay times as the depth increases [Fig. 3(b)]. This is due to the receding presence of the effective thermal source at the back interface as a result of coherent heat accumulation there.

D. Binary phase coding thermal coherence tomography (BPC-TCT)

Binary phase coding is another pulse compression technique that is widely used in radar sciences. While LFM excitation preserves a relatively constant power within the chirp frequency range, BPC modulation leads to a distinct energy localization advantage which is especially useful in diffusive fields. A comprehensive study on BPC can be found elsewhere.\(^{39,56}\)

The BPC signal is formed by multiplying a single frequency carrier and a binary coded envelope in the time domain, or by convolving these two signals in the frequency domain [Fig. 4]. Then, the BPC signal excites the sample surface, and the stimulated thermal response gets recorded by the IR camera. Similar to TWR, the BPC-TCT images are constructed by first cross-correlating the photothermal signal and the excitation signal, and then by measuring the amplitude [Eq. (12)] and the phase [Eq. (13)] of the cross-correlation results.

\[
A_{CC}(\tau) = \frac{1}{f^{-1}[R(\omega)^* \times S(\omega)]},
\]

(12)

\[
\varphi_{cc}(\tau) = \tan^{-1}\left(\frac{\frac{1}{f^{-1}[R(\omega)^* \times S(\omega)]}}{\frac{1}{f^{-1}[R(\omega)^* \times S(\omega)]}}\right),
\]

(13)

where \( R(\omega) \) and \( S(\omega) \) are the Fourier transforms of the reference/modulation signal, \( R(t) \), and the photothermal signal, \( s(t) \). \( f^{-1}, \times, \text{sgn}(\omega), \) and \( i \) denote the inverse Fourier transform, complex conjugation operator, signum function, and imaginary unit, respectively. Experimental results demonstrate that TCT imaging with the same modulation frequency and experimental conditions (averaging, laser power, etc.) maintains a better depth resolution than lock-in thermography.\(^{39,57}\)

An example of TCT imaging of teeth matrix is provided in Fig. 5. The red rectangle shows the imaging area which covers a contacting surface between two teeth being demineralized to simulate early interproximal caries. LIT and TCT phase images [Figs. 5(b) and 5(c)] are formed under identical experimental conditions. TCT exhibits better axial resolution
over LIT, because matched-filter thermography yields higher localization of diffusive fields.

**E. Chirped pulse photothermal radar (CPPTR)**

CPPTR with superior depth probing over PPTR and an improved sensitivity over the harmonically modulated TWR combines pulsed chirp heating with the match-filtering technique.\(^{17,18}\) The reconstruction scheme of CPPTR is shown in Fig. 6 which is similar to the match-filtering thermography techniques presented in Secs. III C and III D. The signal processing method cross-correlates the excitation signal and the response thermal transient in the frequency domain for fast computation. Then, amplitude and phase are calculated using Eqs. (12) and (13), respectively.

This method exhibits improved SNR by minimizing the static (dc) component of the photothermal signal and making use of the Planck radiation emission nonlinearity. The SNR of three excitation waveforms (sine-wave, square-wave, constant width pulses) chirping the pump laser under identical exposure energy for various chirp energies was measured.\(^{18}\) The study proved that among the three distinct chirped excitation waveforms, constant-width pulse chirp with chirp energy lower than 100 mJ exhibits SNR improvement up to two orders of magnitude compared to all other equal energy modalities [Fig. 7].\(^{17}\) The generated photothermal signal has dynamic (ac) and static temperature rise (dc background) components, the latter being cumulative in nature over several repetition cycles. Compared to CW excitation, pulsed signals minimize the static component of the photothermal signal resulting in greater SNR.

**F. Truncated-correlation photothermal coherence tomography (TC-PCT)**

Detection of depth-integrated distributions of energy is a shortcoming intrinsically characteristic of diffusion-wave fields. When 3D visualization of the sample is required, this is a serious limiting factor.\(^{23}\) Truncated-correlation photothermal coherence tomography (TC-PCT),\(^{40}\) and enhanced TC-PCT\(^{26}\) as recently introduced, is the only dynamic thermal imaging modality to-date that provides axially resolved 3D images of materials and tissues.

The TC-PCT signal processing algorithm and examples of reference signals \(\left( R_0 \right) \) and the thermal response signal \(\left( S \right) \) are shown in Figs. 8(a) and 8(b), respectively. In the TC-PCT technique, a generated LFM pulsed chirp excitation signal is employed to produce the in-phase reference signal \(\left( R_0 \right) \) and its quadrature \(\left( R_0^* \right) \). First, the excitation waveform is passed through a square–wave chirp, and then a delay-incremented unit \(\left( C_{1f,0} \right) \). Next, the delay-incremented square-chirp is transmitted through a frequency doubler \(\left( C_{2f,0} \right) \), and the delay-incremented square-chirp \(\left( C_{1f,0} \right) \) and its doubled frequency waveform \(\left( C_{2f,0} \right) \) are subjected to the binary exclusive-OR (EX-OR) operation to produce a

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**FIG. 8.** Enhanced TC-PCT algorithm. (a) Enhanced TC-PCT reconstruction algorithm, and amplitude and phase measurements; (b) An example of the shape of the first and the second truncated reference pulses \(\left( R_{1,0} \right) \) and \(\left( R_{2,0} \right) \), and the photothermal chirp signal \(\left( S \right) \). The time scales for reference signals are not the same as the thermal transient signal; they are exaggerated so as to show the duration of the optical pulse.\(^{26}\)
quadrature square chirp. The reference signal \( R_0 \) and its quadrature \( R_{90} \) are then synthesized from \( C_{1f,0} \) and \( C_{1f,90} \), respectively. In contrast to CPPTR where the Hilbert transform is used to produce the quadrature of the chirp signal, TC-PCT uses the EX-OR operator to avoid generating spikes at the rising and falling edges of the rectangular pulses of the quadrature chirp waveform. In TC-PCT, similar to CCPTR and TWR, the reconstruction of the photothermal signals is based on the cross-correlation technique and is performed in the frequency domain for fast calculation. Then, the cross-correlation amplitude and phase are constructed from the expressions

\[
A_{cc,n} = \sqrt{\left( \mathcal{F}^{-1}[R_n(\omega)] \times S(\omega) \right)^2 + \left( \mathcal{F}^{-1}\{-i\text{sgn}(\omega) R_n(\omega)\} \times S(\omega) \right)^2}
\]

(14)

and

\[
\varphi_{cc,n} = \tan^{-1}\left( \frac{\mathcal{F}^{-1}\{-i\text{sgn}(\omega) R_n(\omega)\} \times S(\omega)}{\mathcal{F}^{-1}[R_n(\omega)] \times S(\omega)} \right).
\]

(15)

The time gating unit in the enhanced TC-PCT algorithm filters the cross-correlation amplitude and phase which is measured for every reference signal \( R_n \) and the photothermal response \( S \), with the following time gating width:

\[
\text{Time gating width} = \text{Shortest pulse distance} - (n - 1) \times d,
\]

(16)

where “the shortest pulse distance” is the distance between the last two consecutive pulses in the full duration of the up-chirp excitation waveform, \( n \) is the TC-PCT slice number, and \( d \) is the constant delay applied to the reference signal by the delay incremented unit. Generally, the constant delay \( d \) has the same value as the slice width shown in Fig. 8(b) with the \( W_T \) label. Axial resolution in the 3D TC-PCT image of the sample depends on this slice width (\( W_T \)). To achieve high axial resolution, a small slice width should be selected which, however, localizes less energy within the slice thickness thus leading to lower TC-PCT signal quality. The minimum value for the \( W_T \) is limited by the camera frame.
rate, and the maximum value is limited by the time difference
between the last two pulses in the up-chirp waveform.

The amplitude peak value and the time corresponding to
the peak value produce the amplitude and amplitude delay
information, respectively. From the cross-correlation phase
[Eq. (15)], the phase value at the amplitude peak time pro-
vides the phase of one pixel. From the resulting cross-
**correlation phase, the time corresponding to zero phase value
provides the phase delay data of one pixel and specifies the
net thermal flux of zero. For all pixels of the captured pho-
**tothermal images, the truncation process provides tomographic
slice TC-PCT amplitude, amplitude peak delay time, phase,
and zero-delay phase planar images (tomograms) of an opti-
cally excited solid. Consequently, TC-PCT analysis provides
four output channels: amplitude, peak delay time, phase,
and zero-delay phase. By stacking depth-scaled planar images
generated through phase incrementing the reference, TC-PCT
can create three dimensional visualizations of the distribution
of the object’s photothermal parameters similar to OCT.

**IV. THERMAL-WAVE IMAGING APPLICATIONS**

**A. Condition monitoring of industrial materials and art
objects—Non-destructive testing**

The use of non-destructive techniques is essential in
industries where the failure of a component would cause a sig-
nificant hazard or economic loss. Thermography has found
many applications for maintenance inspections of industrial
components and structures. LIT, PPT, and TWR are utilized
in imaging hidden structures and defect detection within a
short time in various objects such as steel,8,38,58 aluminum,59
ceramics,49,60 composites,61 carbon fiber reinforced plastics
(CFRP),55,62 wood,49 Nylon®,63 and concrete structures.64
These thermal imaging technologies can accurately determine
cracks, holes, or defects in a piece of material, which is impor-
tant information for quality control to prevent breakdowns. An
example of defect detection in aluminum is shown in Fig. 9.
Two flat concentric bottom holes are drilled in a thick alumi-
num plate, one at the center of the other [Fig. 9(b)], and then
imaged. PPT signal processing using wavelet transformation
was applied to reconstruct the image shown in Fig. 9(a).51

Active thermography was successfully applied to investi-
gations of the structure of paintings, subsurface delamination,
and the degree of adhesion between paint layers.11,65–67 In
the field of art analysis, TC-PCT was applied to image the
defective regions in a marquetry sample and successfully
revealed holes, wood knots, glue rich areas, wood grain of
the supporting layer of the marquetry, and delaminations.68

**B. Medical applications—Biothermophotonics**

Biomedical photothermics (“biothermophotonics”) is an
emerging non-ionizing, non-invasive diagnostic methodology
based on spectrally selective optical absorption of modulated
(or pulsed) electromagnetic radiation, thermal (non-radiative)
conversion, and generation of thermal waves in tissues. Medical
applications of thermophotonics are steadily growing since the
sensitivity and specificity of these methods are inherently
high.69,70 Reports show the applicability of thermography

techniques to biological tissues. However, the constraints
imposed by the laser safety ceiling and the strong attenuation
of thermal wave signals in tissues limit the detection depth in
turbid media and tissues.28,29 For example, in PPT, where a
single pulse excitation is used and raw data are not processed,
subsurface absorber detection in turbid media and tissues is
limited to ∼1 mm.30,31 The main concern with applying therm-
ography techniques to biological tissues lies in its limitations
to resolve deep lying absorbers over a depth of a few

![FIG. 11. Three-dimensional non-destructive enhanced TC-PCT imaging.]({#fig11})
Amplitude tomograms of the enhanced TC-PCT of holes at the depth of 0.4
mm (a), 0.6 mm (b), and 1 mm (c) with truncation time gate of 40 ms. Each
image covers an area of 2.1 cm x 1.68 cm on the sample, and the image
delay time range is 1.2 s which corresponds to the depth of 4.39 mm. The
z = 0 plane at the bottom of the image is the coordinate at which the camera
recorded the thermal signals. A and B on these images display the holes, and
the energy accumulation at the back surface, respectively. The images on
(a)–(c) are not on the same scale. The laser beam illuminating the sample
from the bottom is a pulsed chirped signal with a sweep range of 0.2 Hz–0.6
Hz, duration 12 s, and pulse duration 10 ms. Diameter of the illumination
beam is 3 cm, and the laser intensity for the whole duration is 7 mJ/cm².26
The first attempt in characterizing cortical bone with the aim of establishing a thermal imaging technology for the early diagnosis of osteoporosis was the development of CPPTR.  The skin and tissue overlayers strongly attenuate thermal waves generated in bones as a result of weak conductive thermal coupling between the bone and the skin surface. Additionally, re-absorption of emitted IR-photons by water molecules in the overlying tissues may occur, which forbids radiative coupling. CPPTR with superior SNR and depth profiling capability over the harmonically modulated TWR and PPTR was applied to monitor the degree of demineralization in a goat rib bone with overlayers of fat and skin. The largest bone thickness resolvable using CPPTR was \(1.8\) mm with a skin-fat overlayer of \(1\) mm thickness. Later, TC-PCT was applied to imaging the structure of bones [Fig. 10]. TC-PCT demineralization tracking has been carried out to a depth of \(3.6\) mm below the irradiated surface. Since the skin overlay of a typical human wrist is in the range of \(0.8-2\) mm, it is feasible to apply TC-PCT or even CPPTR to the diagnosis of human bone density for inspection of the wrist.

TC-PCT use has grown in a variety of applications from imaging subsurface defects and discontinuities in solids and defectoscopy in art objects to medical applications such as imaging burn depth profiles in tissues. For NDI applications, TC-PCT provided defect detection in a steel sample at the depth of \(4\) mm, while lock-in thermography and the TWR reported maximum depth probing of \(1.5\) mm in the steel sample for the same imaging parameters. A few examples of TC-PCT images of bone, holes in a steel sample, and burn depth profiles are presented in Figs. 10–12, respectively. Figure 10(a) shows TC-PCT amplitude planar images of a goat rib sampled at 20 ms reference-delay intervals.

Figure 10(b) displays binarized amplitude TC-PCT compared with micro-computed tomography (\(\mu\)CT) images of the goat rib sample before and after demineralization. Figure 11 displays three holes at different depths in a steel sample. Application of TC-PCT to depth analysis of three burns in a pig’s ear is shown in Fig. 12.

TC-PCT is the thermophotonic analog of OCT with better penetration depth in tissues (~3.6 mm in bones and more than 3.8 mm in teeth). Although OCT offers high resolution images, its probe range is limited to less than 1 mm in bones, because of the highly scattering nature of light in hard tissues. In contrast to photoacoustic imaging, which combines optical excitation and ultrasound detection, TC-PCT offers higher resolution, particularly in hard tissues. Photoacoustic imaging performs poorly with bone tissues due to severe attenuation of optical and ultrasound signals within bone structures, especially at higher frequencies that are necessary for enhanced resolution. Axial resolution of photoacoustic imaging in bone diagnostics is in the range of 1 mm, while axial resolution of TC-PCT in bone imaging was measured to be \(\sim 25\) \(\mu\)m.

V. CONCLUSIONS AND OUTLOOK

With rapid improvements in the quality of infrared cameras over recent years, thermal imaging is attracting growing attention in biomedical applications and in the field of NDI of industrial materials and art analysis. In thermal wave imaging, energy conversion occurs between optical and thermal modes. Therefore, the specificity of the technique is inherently high because of its optical contrast, and its sensitivity is also high due to the energy conversion suppression of signal baselines which impart it with higher dynamic range than purely optical imaging modalities. Furthermore,
thermal-wave detection is very suitable for imaging turbid media such as biological tissues because it is not subject to resolution and depth-limiting optical and/or ultrasound scattering mechanisms.

Used for characterizing bone structures, diagnosing dental caries, visualizing burn depth profiles in tissue, and detecting photothermal imaging (which also includes conventional thermography) has been proven to be a safe, reliable, sensitive, non-destructive, and non-contacting method for defect detection and structure studies. Thermal-wave analysis requires a modest amount of harmless optical radiation deposited onto a sample and is safer than X-rays. Therefore, we can reasonably expect rapid growth in the number of applications in wide ranges of fields from biomedical, industrial, dental, to artwork NDI.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council (NSERC) Discovery Grants Program, the Canada Research Chairs Program, a CIHR-NSERC CHRP Grant to A. Mandelis for TC-PCT dental imaging applications, and the NSERC—Collaborative Research and Training Experience (CREATE) for financial support.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>BPC</td>
<td>Binary phase coding</td>
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<tr>
<td>CFRP</td>
<td>Carbon fiber reinforced plastic</td>
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<td>CPPTR</td>
<td>Chirped pulse photothermal radiometry</td>
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<tr>
<td>CW</td>
<td>Continuous wave</td>
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<tr>
<td>EX-OR</td>
<td>Exclusive-OR</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<tr>
<td>HT</td>
<td>Hilbert Transform</td>
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<tr>
<td>IFFFT</td>
<td>Inverse FFT</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
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<td>LFM</td>
<td>Linear frequency modulation</td>
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<tr>
<td>LIT</td>
<td>Lock-in thermography</td>
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<td>MPE</td>
<td>Maximum-permissible exposure</td>
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<tr>
<td>NDI</td>
<td>Non-destructive imaging</td>
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<td>OCT</td>
<td>Optical coherence tomography</td>
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<tr>
<td>PPT</td>
<td>Pulse phase thermography</td>
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<tr>
<td>PPTR</td>
<td>Pulse photothermal radiometry</td>
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<tr>
<td>PRBS</td>
<td>Pseudorandom binary sequence</td>
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<td>PT</td>
<td>Pulsed Thermography</td>
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<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
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<td>TCT</td>
<td>Thermal coherence tomography</td>
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<tr>
<td>TWR</td>
<td>Thermal wave radar</td>
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<tr>
<td>TC-PCT</td>
<td>Truncated-correlation photothermal coherence tomography</td>
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<tr>
<td>μ-CT</td>
<td>Micro-computed tomography</td>
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