International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Operating Publisher
SciFormat Publishing Inc.
ISNI: 0000 0005 1449 8214

2734 17 Avenue SW,
Calgary, Alberta, T3E0A7,
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ARTICLE TITLE	ULTRASONIC MEASUREMENTS OF TISSUE TEMPERATURE: POTENTIAL CLINICAL APPLICATIONS
DOI	https://doi.org/10.31435/ijitss.2(50).2026.5492
RECEIVED	25 March 2026
ACCEPTED	25 June 2026
PUBLISHED	30 June 2026
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ULTRASONIC MEASUREMENTS OF TISSUE TEMPERATURE: POTENTIAL CLINICAL APPLICATIONS

Patrycja Lipska *(Corresponding Author, Email: lipskapatrycja7@gmail.com)*
Faculty of Medicine, Wroclaw Medical University, Wroclaw, Poland
ORCID ID: 0009-0002-3351-2312

Pawel Iwaszkiewicz
T. Marciniak Lower Silesian Specialist Hospital in Wroclaw, Wroclaw, Poland
ORCID ID: 0009-0001-5106-566X

Ivanna Lazarchuk
Regional Specialist Hospital, Wroclaw, Poland
ORCID ID: 0009-0000-1104-0794

Robert Iwanowski
Regional Health Centre in Lubin, Lubin, Poland
ORCID ID: 0009-0001-1401-1996

Alina Porubenska
Faculty of Medicine, Wroclaw Medical University, Wroclaw, Poland
ORCID ID: 0009-0007-9913-9350

Paulina Kalemba
Faculty of Medicine, Wroclaw Medical University, Wroclaw, Poland
ORCID ID: 0009-0000-5856-1271

Zuzanna Lepa
Medical Care Centre, Jaroslaw, Poland
ORCID ID: 0000-0001-8499-7458

Julia Pająk
4th Military Clinical Hospital with Polyclinic, Wroclaw, Poland
ORCID ID: 0009-0007-0882-9365

Antoni Majda
Regional Specialist Hospital, Wroclaw, Poland
ORCID ID: 0009-0006-4357-513X

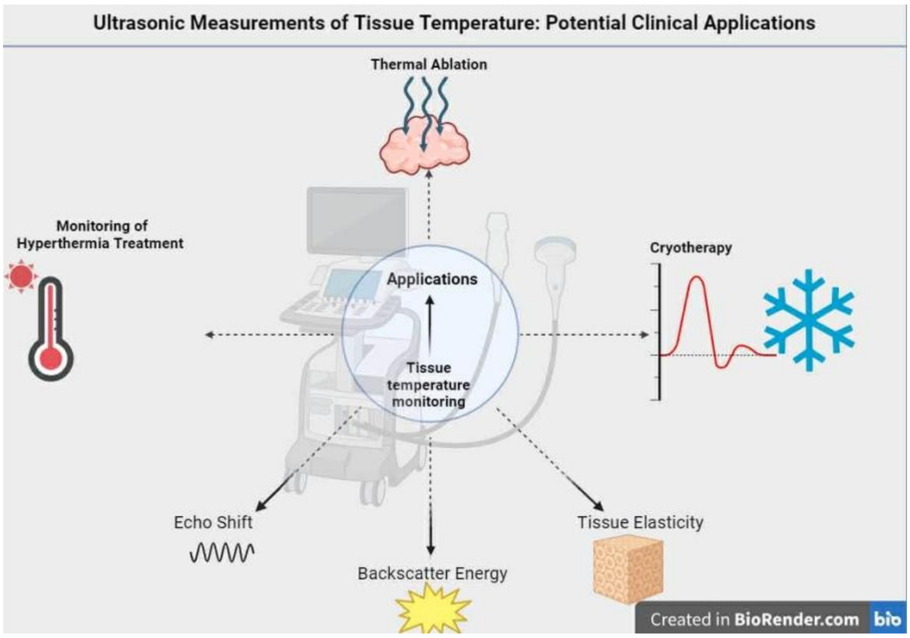
Anna Kamosińska
4th Military Clinical Hospital with Polyclinic, Wroclaw, Poland
ORCID ID: 0009-0005-0718-2112

Adam Kowal
Jan Mikulicz Radecki University Clinical Hospital, Wroclaw, Poland
ORCID ID: 0009-0007-7779-598X

Veronika Porubenska
Faculty of Dentistry, Wroclaw Medical University, Wroclaw, Poland
ORCID ID: 0009-0005-3409-3086

ABSTRACT

In recent years, significant advancements have been made in the field of ultrasonographic technology. One of the most promising applications of ultrasonographic technology is its ability to measure tissue temperature. Ultrasonic measurement of tissue temperature represents a rapidly evolving extension of conventional ultrasonography, necessitating a thorough review and synthesis of current methodologies and potential clinical applications to support its effective implementation in clinical practice. A comprehensive literature review was carried out using PubMed, Scopus, and Google Scholar to explore ultrasonic methods for measuring tissue temperature and their clinical relevance. To ensure both historical context and insight into current advancements, the analysis covered 36 studies published between 1979 and 2022. Changes in wave speed, backscatter energy and local tissue elasticity can be used to monitor the tissue temperature. The measurements have demonstrated significant potential in a variety of clinical applications owing to their non-intrusive characteristics and ability to provide real-time monitoring. These applications include monitoring of hyperthermia treatment, thermal ablation, and cryotherapy, where tissue temperature measurement allows for optimal heating or cooling of target tissues, enhancing treatment precision and minimizing damage to surrounding structures. This review presents an in-depth overview of ultrasonic tissue temperature assessment, covering its underlying physical principles, measurement techniques, and possible clinical uses.



KEYWORDS

Ultrasonography; Thermometry; Elasticity Imaging Techniques; Hyperthermia Induced; Ablation Techniques; Cryotherapy

CITATION

Patrycja Lipska, Pawel Iwaszkiewicz, Ivanna Lazarchuk, Robert Iwanowski, Alina Porubenska, Paulina Kalemba, Zuzanna Lepa, Julia Pająk, Antoni Majda, Anna Kamosińska, Adam Kowal, Veronika Porubenska. (2026) Ultrasonic Measurements of Tissue Temperature: Potential Clinical Applications. *International Journal of Innovative Technologies in Social Science*. 2(50). doi: 10.31435/ijitss.2(50).2026.5492

1. Introduction

In recent years, ultrasonic technology has made significant advancements, particularly in the field of medical diagnostics and therapeutic interventions. One of the most promising applications of ultrasound technology is its ability to measure tissue temperature, which has significant clinical implications. There are two types of imaging techniques used for monitoring tissue temperature: invasive techniques like thermocouples, Fiber Bragg Gratings (FBG), thermisters, and non-invasive techniques like magnetic resonance (MR) imaging, computed tomography (CT), ultrasound (US), and infrared imaging (IR)(Blouin et al., 1991; Germer et al., 1997; Ishihara et al., 1995; Nasoni et al., 1979; Tosi et al., 2018).

The almost precise monitoring of tissue temperature in real time offers a wide range of potential applications across various medical specialties. In the clinical setting, it helps to guide and optimize various therapeutic interventions. In the field of oncology, precise temperature monitoring during thermal ablation procedures, like radiofrequency or microwave ablation, can help ensure effective tumor destruction while minimizing damage to surrounding healthy tissues(Y.-D. Liu et al., 2017; Peng et al., 2021; Seo et al., 2011). Comparing USG to MRI, ultrasound is portable, more accessible, affordable, and compatible with other medical equipment(Li & Wu, 2013). This study aims to review the theoretical basis and the practical and potential clinical applications of ultrasonic measurements for tissue temperature monitoring.

2. Theoretical basis

Ultrasonography is one of the most frequently used clinical imaging techniques(Birkeland et al., 2014; Moran & Thomson, 2020; Rix et al., 2018). It utilizes the piezoelectric effect to generate high-frequency sound waves that are transmitted to an examined body by a probe. Sound waves penetrate tissues and reflect off the structures that they encounter. The amount of reflection depends on the difference in the acoustic impedances of the two tissues. Acoustic impedance can be expressed as the product of tissue density and sound wave speed. Therefore, a greater tissue density difference usually results in a greater amount of reflected sound. A reflected sound, called an echo, is received, and transformed into electrical signals by the transducer(Grogan & Mount, 2022). The frequency of ultrasound waves impacts the resolution and penetration depth of the imaging. Ultrasound frequencies used in imaging vary from 2 to 15 MHz. High-frequency ultrasound waves provide high-resolution images but are limited in penetration depth, making them suitable for imaging superficial tissues. In contrast, low-frequency ultrasound waves penetrate deeper into the body but offer lower resolution(Grogan & Mount, 2022; Murphy & Nadrljanski, 2005). Changes in tissue temperature affect some of the ultrasonography parameters, such as wave speed, backscatter energy and changes in local tissue elasticity. This fact can be used to measure tissue temperature(Straube & Arthur, 1994; Techavipoo et al., 2004).

3. Echo shift

The distance of a structure from the transducer presented in the ultrasound images is determined based on the time taken for the sound wave to reach the structure and then return to the transducer. This method assumes a constant wave-propagation velocity. However, as mentioned earlier, the sound wave velocity depends on tissue temperature(Bamber & Hill, 1979; Nasoni et al., 1979). The described phenomenon appears as a shift of an echo. The echo shift is also affected by the thermal expansion of the tissue(Seip & Ebbini, 1995). It has been shown that in tissues with low fat content, the speed of sound increases with temperature until it reaches a maximum at 50 °C, whereas in fat-rich tissues, a negative dependence is observed(Bamber & Hill, 1979). The echo shift effect can be used to monitor the temperature of tissues undergoing thermal therapy. Theoretical models predict an approximately linear relationship between these shifts and tissue temperature rise, which has been proven experimentally. Assuming negligible thermal expansion, the temperature change can be expressed as:

$$\Delta T(z) = k \frac{v(z, T_0)}{2t(z)}$$

Where z is the depth, k is the tissue-dependent coefficient, $v(z, T_0)$ represents the wave speed at depth z and the initial temperature T_0, and $t(z)$ is the measured time shift of the echos(D. Liu & Ebbini, 2009; Simon et al., 1998).

4. Backscatter energy

The amount of backscattered energy depends on the acoustic properties of the tissue. This means that it also indirectly depends on the tissue temperature. Straube WL et al. developed a model that relates the change in temperature and the change in backscattered energy (CBE)(Straube & Arthur, 1994). According to the model, CBE is primarily dependent on the change in the backscatter coefficient due to temperature. The backscatter coefficient is influenced by the compressibility and density of the scatterers and the medium, among other factors, and therefore it is also influenced by the type of tissue. Arthur RM et al. showed that the monitoring of CBE can be successfully used to predict temperature changes in the range of 37 °C to 50 °C(Arthur et al., 2003, 2008). They demonstrated that the change in backscattered energy (CBE) with temperature is nearly monotonic. This means that as the temperature increases, the CBE generally increases or decreases in a consistent manner without large fluctuations. The CBE map can be generated from B-mode images by squaring and averaging with a moving average filter and then comparing it to the backscattered energy map generated based on the reference image(Arthur et al., 2008).

5. Local tissue elasticity

Tissue mechanical behavio rcan be characterized by the Young'smodulus:

$$E = \frac{9K\mu}{3K + \mu}$$

where E is the Young's modulus, K is the inverse of the compressibility (the bulk modulus) and μ is the shear modulus. The bulk modulus does not change notably with changes in temperature or tissue type, whereas the shear modulus is highly dependent on the tissue type and changes during thermal ablation due to tissue coagulation and other structural changes(Sapin-de Brosses et al., 2010; Wu et al., 2001). Hence, elastography measurements can be used to monitor tissue temperature in ablation procedures. It is worth noting that during thermal ablation, the shear modulus heating and cooling curves differ because of irreversible changes in the tissue, therefore this method has some limitations. The shear modulus can be calculated using the measurements of the shear wave velocity c_s:

$$\mu = \rho c_s^2$$

where μ is the shear modulus, and ρ is the material's density. Shear waves can be generated by focusing the ultrasonic beams at different depths for a short period of time(Sapin-de Brosses et al., 2010).

6. Ultrasonic measurements in practice

Various ultrasound techniques have been suggested for determining temperature changes in tissue. These methods are based on different changes in the ultrasound properties that are caused by temperature, such as changes in frequency-dependent attenuation, backscattered power, sound velocity, thermal expansion, or a combination of the latter two effects(Clarke et al., 2003; Varghese et al., 2002; Worthington et al., 2002).

Studies analyzing changes in US properties have typically focused on temperatures below 40ºC(Bamber & Hill, 1979). However, some studies have explored changes at higher temperatures, with a few evaluating up to 80ºC(Clarke et al., 2003; Varghese et al., 2002; Worthington et al., 2002). Only one study by Varghese et al has monitored temperature changes up to 100ºC(Varghese et al., 2002). In contrast, M. Mokhtari-Dizaji et al. assessed the temperature range from 25ºC to 95ºC, making it the study with the widest range of temperatures assessed(Mokhtari-Dizaji et al., 2007). High thermal sensitivity is required for detecting small variations in tissue temperature with the thermal imaging method, due to the relatively low physiological variability in tissue temperature ranging between 36.5°C and 37.5°C. After exposure to high temperatures, tissue can undergo carbonization which increases US absorption and affects the quality of US B-mode(Mokhtari-Dizaji et al., 2007).

Practical measurements can be affected by the variation in speed of sound with temperature, which causes pixel shifts and apparent or virtual shifts in the scatter positions and time shifts into the received echo signals. According to M. Mokhtari-Dizaji et al, the maximum pixel shift occurs between 60 to 70ºC. They also suggest that if the temperature increases moderately, it will be possible to monitor and save the ultrasound B-mode images for each 10ºC temperature rise(Mokhtari-Dizaji et al., 2007).

To our knowledge, most studies focused on B-mode images(Y.-D. Liu et al., 2017; Mokhtari-Dizaji et al., 2007; Varghese et al., 2002). On the other hand, Manaf et al. proposed the use of A-mode ultrasound as a means of monitoring temperature changes during local hyperthermia treatment. They found that A-mode ultrasound is highly sensitive to changes in tissue microstructure during hyperthermia, making it an effective monitoring tool. Additionally, 1D ultrasound can provide real-time monitoring to guide the process of local hyperthermia treatment. This method could allow for faster and simpler quantitative measurements compared to other methods, especially when compared to the 2D ultrasound monitoring system(Manaf et al., 2016).

The average grey levels (AVGL) is yet another verified method based on B-mode images for tracking temperature variation(Teixeira et al., 2014). The AVGL, proposed by Alvarenga et al, showed that values varied more in the muscle tissue image region than in the fat tissue image region, for the same temperature range(Alvarenga et al., 2020). According to their findings, the average changes in temperature and AVGL in the studied tissues (fat and muscle) are not affected by the path taken by ultrasound waves through different tissues. This suggests that a single B-mode image and the corresponding relationship between AVGL and temperature in each region can be used to estimate temperature changes in various tissue regions without the need for invasive methods.

According to the experiments conducted by Wang X. et al. on the porcine liver, it has been found that there is another parameter that can be used to determine tissue temperature. This parameter includes gray level histogram (GLH), gray level co-occurrence matrix (GLCM), and gray level-gradient co-occurrence matrix (GGCM). Their study found that some of these parameters achieved correlation coefficients higher than 0.9 when the tissue temperature changed from 20°C to 60°C thus providing a chance of their potential practical usage(Wang & Sheng, 2022).

7. Potential clinical applications

Ultrasonic measurements of tissue temperature have demonstrated significant potential in a variety of clinical applications due to their non-intrusive characteristics and ability to provide real-time monitoring(Manaf et al., 2016). Potential clinical applications of this technology are outlined below.

7.1. Hyperthermia Treatment Monitoring

Hyperthermia involves deliberately raising the temperature of a specific area of the body to enhance the effects of treatments such as radiation therapy or chemotherapy(Manaf et al., 2016). Information about the tissue is conveyed through ultrasonic scattered echoes, and alterations in tissue temperature can impact the properties of these echoes. Employing statistical analysis of these echoes enables the estimation of temperature changes within the tissue(Takeuchi et al., 2020). The potential of utilizing A-mode ultrasound attenuation as a monitoring technique for local hyperthermia treatment has been investigated to assess its feasibility(Manaf et al., 2016).

In a certain area where hyperthermia is used, local heating is provided. Ultrasonic suppression in Mode A is used to measure temperature changes in the target area. It is a non-invasive monitoring technique, safe and further eliminates the need for invasive procedures. The real-time monitoring capabilities of an ultrasound provide continuous feedback during a hyperthermia session, ensuring that the intended temperature is reached and maintained in the treated tissue. With its commendable spatial resolution, mode ultrasounds facilitate meticulous monitoring of temperature changes at a localized scale. It is necessary to recognize that variations in tissue composition and structure can affect the suppression of ultrasound, emphasizing the importance of taking these changes into account for accurate temperature assessment. The application of A-mode ultrasound attenuation extends to thermal ablation procedures, such as radiofrequency ablation (RFA) or high-intensity focused ultrasound (HIFU), particularly in situations where maintaining precise temperature control is paramount(Manaf et al., 2016).

7.2. Thermal Ablation Procedures

Harmonic motion imaging for concentrated ultrasound (HIFU) is a recommended procedure that combines two methods of concentrated ultrasound to direct thermal ablation and simultaneous monitoring of a single tissue. The HIFU closely directs the high-frequency flame to induce controlled heating in specific tissues, resulting in intentional tissue ablation. The approach incorporates harmonic motion imaging to observe and analyze the harmonic vibrations generated within the tissue in response to the ultrasound waves. During the process, focused ultrasound is applied to the target tissue, converting the ultrasound-generated energy into heat, ultimately causing tissue coagulation or necrosis. HMIFU finds frequent use in tumor ablation, leveraging the accuracy of targeted ultrasound waves for the eradication of cancerous cells. As a non-invasive surgical technique, HMIFU enables precise tissue treatment without the necessity for traditional surgical incisions(Maleke & Konofagou, 2008).

7.3. Cryotherapy Monitoring

Cryotherapy is a method of using extremely low temperatures to treat various diseases. The process involves spraying liquid nitrogen or other cryogenic substances directly onto the target tissue, leading to the freezing and elimination of abnormal cells. Cryotherapy is commonly used to treat precancerous lesions, tumors and abnormal blood vessels. Notably, cryotherapy enables accurate targeting of specific problem areas while preserving the health of surrounding tissues(Johnston, 2003).

Superb Microvascular Imaging (SMI) represents a sophisticated ultrasound imaging method specifically crafted to augment the clarity of microvascular structures within tissues. This technology enhances sensitivity in detecting blood flow, thereby assisting in the evaluation of vascularity throughout medical procedures. The utilization of ultrasound monitoring in cryotherapy facilitates the ongoing, real-time evaluation of the freezing process and its repercussions on the designated tissue. This practice guarantees precise targeting and comprehensive coverage of the intended treatment region(Matsugasumi et al., 2022).

8. Conclusions

In recent years, ultrasound technology has made extremely important advances, offering huge potential in both medical diagnosis and therapeutic interventions. Ultrasonic temperature measurement has proven to be a particularly promising application with a wide range of clinical implications. Ultrasound has a variety of uses, ranging from monitoring the temperature of tissues during hyperthermia treatments to conducting thermal ablation procedures and cryotherapy.

Ultrasound measurements play a key role in optimizing therapeutic outcomes while ensuring patient safety. In addition, advances such as the integration of excellent microvascular imaging (SMI) further enhances the precision and effectiveness of ultrasound-based therapies. SMI enables clear visualization of microvascular structures, facilitating real-time assessment during cryotherapy procedures.

Artificial intelligence (AI) has the potential to improve temperature monitoring by adjusting thermal energy delivery in real-time and integrating temperature data into personalized treatment plans. AI can also be utilized to create models that more accurately predict tissue temperature based on ultrasound images. However, no published studies have been found on this topic, so it is recommended to conduct further research to explore this application.

If a technique for measuring temperature and not its changes could be developed, it might be used in the diagnosis of inflammation, cancer, or monitoring deep body temperature. In addition, further research is needed to clarify the unified mechanism of action underlying ultrasound therapy, which may pave the way for optimizing treatment parameters and realizing more consistent positive outcomes.

Ultrasonic measurements used to monitor the temperature of tissues hold great promise in various medical specialties, such as oncology (hyperthermia therapy and thermal ablation), interventional radiology (real-time monitoring during ablation procedures), and urology and gastroenterology (guidance and monitoring in cryotherapy). Continued research and technological innovation in this field - particularly the integration of artificial intelligence for image analysis and temperature estimation - are expected to drive significant progress. These advancements have the potential to enhance treatment precision, improve patient safety, and ultimately lead to better clinical outcomes.

Ethics Approval: The study was a descriptive one. No humans or animals were a subject of examinations.

Conflicts of Interest: The authors state no conflict of interest.

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