(54) **METHOD AND SYSTEM FOR DETERMINING AT LEAST ONE PARAMETER OF INTEREST OF A MATERIAL**

VERFAHREN UND SYSTEM ZUR BESTIMMUNG MINDESTENS EINES ZU UNTERSUCHENDEN PARAMETERS EINES MATERIALS

PROCÉDÉ ET SYSTÈME DE DÉTERMINATION D'AU MOINS UN PARAMÈTRE D'INTÉRÊT D'UN MATÉRIAU

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Description

Field

5   **[0001]** The subject disclosure relates to thermoacoustic imaging and in particular to a method and system for determining at least one parameter of interest of a material.

Background

10   **[0002]** Materials can be identified or quantified by making one or more measurements of the material and as a result, if the type of material is unknown, identification or quantification methods can be performed to identify the material. These methods often require the use of specialized equipment. For example, dielectric measurement systems require a specialized probe and network analyzer.

[0003] In medical settings such as in a hospital, this specialized equipment may not be readily available. As will be
15   appreciate, if required, it is desirable to determine at least one parameter of a material using equipment that is readily available in a medical setting. Document US2017/273730 (Walke AJ et al. published on September 28, 2017; Methods and Devices for Energy Delivery and Therapy) discloses the energy delivery devices and methods that have one or more features to measure and estimate the amount delivered to the target material. In addition, methods and devices disclosed are used for calculating the energy dose to be delivered to the target material and delivery of an accurate
20   energy dose to the same. Patent document WO 2019/027496 A1 (ENDRA LIFE SCIENCES INC. published on February 7, 2019) discloses a method and system for estimating fractional fat content of an object of interest. An energy emitter is used to direct an energy signal with an energy signal electric field strength toward the region of interest, wherein the region of interest has an object of interest, a reference, and a boundary between the object of interest and the reference. A thermoacoustic bipolar signal from the boundary is correlated to an electric field strength of the reference at the
25   boundary to generate a corrected thermoacoustic bipolar signal at the boundary, and calculate a fat concentration of the object of interest as a function of the corrected thermoacoustic bipolar signal at the boundary.

[0004] Although techniques for determining at least one parameter of interest of a material have been considered, improvements are desired. It is therefore an object at least to provide a novel method and system for determining at least one parameter of interest of a material.

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Summary

[0005] It should be appreciated that this summary is provided to introduce a selection of concepts in a simplified form that are further described below in the detailed description. This summary is not intended to be used to limit the scope
35   of the claimed subject matter as defined by the appended claims.

[0006] Accordingly, in one aspect there is provided a method for determining at least one parameter of interest of a material, the method comprising directing, using a radio frequency (RF) applicator, one or more RF energy pulses into a region of interest, the region of interest comprising the material having the parameter of interest and at least one reference, the material and the reference separated by at least one boundary; detecting, using an acoustic receiver, at
40   least one multi-polar acoustic signal generated in the region of interest in response to the RF energy pulses; processing the at least one multi-polar acoustic signal to determine an electric field strength at the boundary; calculating a voltage standing wave ratio (VSWR) of the one or more RF energy pulses; and determining the at least one parameter of interest of the material based at least on the determined electric field strength and the VSWR.

[0007] In one or more embodiments, the at least one parameter of interest is one of a Grüneisen Parameter of the
45   material and a conductivity of the material.

[0008] In one or more embodiments, the at least one parameter of interest is a product of the Grüneisen Parameter of the material and the conductivity of the material.

[0009] In one or more embodiments, the at least one parameter of interest is a specific heat capacity of the material.

[0010] In one or more embodiments, an identity of the material is known.

50   **[0011]** In one or more embodiments, the determining comprises estimating the at least on parameter of interest.

[0012] In one or more embodiments, an identity of the material is unknown.

[0013] In one or more embodiments, the determining comprises looking up the at least one parameter of interest in a lookup table.

[0014] In one or more embodiments, the method further comprises monitoring a forward power and a reflected power
55   of the one or more RF energy pulses to calculate the VSWR.

[0015] In one or more embodiments, the electric field strength is determined based on an input power of the RF applicator and an attenuation coefficient of the reference.

[0016] In one or more embodiments, the electric field strength is determined based on an estimated thickness of the

reference and an attenuation coefficient of the reference.

[0017] In one or more embodiments, each multi-polar acoustic signal corresponds to a separate boundary location.

[0018] In one or more embodiments, detecting the at least one multi-polar acoustic signal is achieved using a thermoacoustic imaging system.

[0019] According to another aspect, there is provided a system for determining at least one parameter of interest of a material, the system comprising a thermoacoustic imaging system comprising a radio frequency (RF) applicator configured to emit RF energy pulses into the region of interest comprising a material having at least one parameter of interest and a reference, the material and the reference separated by at least one boundary, and an acoustic receiver configured to receive at least one multi-polar acoustic signal generated in the region of interest in response to the RF energy pulses; and one or more processors configured to: process multi-polar acoustic signals received by the acoustic receiver to determine an electric field strength at the boundary; calculate a voltage standing wave ratio (VSWR) of the one or more RF energy pulses; and determine the at least one parameter of interest of the material based at least on the determined electric field strength and the VSWR.

[0020] In one or more embodiments, the at least one parameter of interest is one of a Grüneisen Parameter of the material and a conductivity of the material.

[0021] In one or more embodiments, the at least one parameter of interest is a product of the Grüneisen Parameter of the material and a conductivity of the material.

[0022] In one or more embodiments, the at least one parameter of interest is a specific heat capacity of the material.

[0023] In one or more embodiments, the system comprises at least one power monitor configured to monitor a forward and reflected power of the RF energy pulses, and the one or more processors are configured to calculate the VSWR using the forward and reflected power of the RF energy pulses.

[0024] In one or more embodiments, the electric field strength is determined based on an input power of the RF applicator and an attenuation coefficient of the reference.

[0025] According to another aspect there is provided a non-transitory computer readable medium having stored thereon computer program code executable by one or more processors to process at least one multi-polar acoustic signal generated in a region of interest comprising a material having a parameter of interest and at least one reference, the material and the at least one reference separated by at least one boundary, to determine an electric field strength at the boundary; calculate a Voltage Standing Wave Ratio (VSWR) of RF energy pulses directed into the region of interest; and determine at least one parameter of interest of the material based at least on the determined electric field strength and the VSWR.

Brief Description of the Drawings

[0026] Embodiments will now be described more fully with reference to the accompanying drawings in which:

FIG. 1 is a schematic view of an imaging system wherein a region of interest is *in vitro*;
FIG. 2 is a graph showing exemplary multi-polar signals generated in response to thermoacoustic imaging of a tissue region of interest comprising different tissue materials separated by a boundary;
FIG. 3 is a graph showing exemplary electric field strength attenuation curves;
FIG. 4 is a graph showing exemplary flux (energy gradient) of RF energy pulses;
FIG. 5 is a flowchart of a method for determining at least one parameter of interest of a material;
FIG. 6 is a flowchart of another method determining at least one parameter of interest of a material;
FIG. 7 is a schematic view of the imaging system wherein the region of interest is *in vivo*;
FIG. 8 is a schematic view of another embodiment of an imaging system.

Detailed Description of the Embodiments

[0027] The foregoing summary, as well as the following detailed description of certain examples will be better understood when read in conjunction with the appended drawings. As used herein, an element or feature introduced in the singular and preceded by the word "a" or "an" should be understood as not necessarily excluding the plural of the elements or features. Further, references to "one example" or "one embodiment" are not intended to be interpreted as excluding the existence of additional examples or embodiments that also incorporate the described elements or features. Moreover, unless explicitly stated to the contrary, examples or embodiments "comprising" or "having" or "including" an element or feature or a plurality of elements or features having a particular property may include additional elements or features not having that property. Also, it will be appreciated that the terms "comprises", "has", "includes" means "including but not limited to" and the terms "comprising", "having" and "including" have equivalent meanings.

[0028] As used herein, the term "and/or" can include any and all combinations of one or more of the associated listed elements or features.

[0029]   It will be understood that when an element or feature is referred to as being "on", "attached" to, "connected" to, "coupled" with, "contacting", etc. another element or feature, that element or feature can be directly on, attached to, connected to, coupled with or contacting the other element or feature or intervening elements may also be present. In contrast, when an element or feature is referred to as being, for example, "directly on", "directly attached" to, "directly connected" to, "directly coupled" with or "directly contacting" another element of feature, there are no intervening elements or features present.

[0030]   It will be understood that spatially relative terms, such as "under", "below", "lower", "over", "above", "upper", "front", "back" and the like, may be used herein for ease of description to describe the relationship of an element or feature to another element or feature as illustrated in the figures. The spatially relative terms can however, encompass different orientations in use or operation in addition to the orientation depicted in the figures.

[0031]   In the following, a method and system for determining at least one parameter of interest of a material are described. The method comprises directing, using a radio frequency (RF) applicator, one or more RF energy pulses into a region of interest, the region of interest comprising the material having the parameter of interest and at least one reference, the material and the reference separated by at least one boundary. An acoustic receiver is used to detect at least one multi-polar acoustic signal generated in the region of interest in response to the RF energy pulses. The at least one multi-polar signal is processed to determine an electric field strength at the boundary. A voltage standing wave ratio (VSWR) of the one or more RF energy pulses is calculated. The at least one parameter of interest is determined based at least on the determined electric field strength and the VSWR.

[0032]   The at least one parameter of interest may be a Grüneisen Parameter of the material, a conductivity of the material, a product of the Grüneisen Parameter of the material and a conductivity of the material, salinity of a material, and/or a specific heat capacity of the material. Practical applications in a body can include estimating fat content in tissue and confirming whether a tumor is benign or malignant.

[0033]   Turning now to FIG. 1, an exemplary imaging system is shown and is generally identified by reference numeral 20. As can be seen, the imaging system 20 comprises a programmed computing device 22 communicatively coupled to an ultrasound imaging system 24 and to a thermoacoustic imaging system 26. The ultrasound imaging system 24 and thermoacoustic imaging system 26 are configured to obtain ultrasound image data and thermoacoustic image data, respectively, of a region of interest ROI.

[0034]   The programmed computing device 22 in this embodiment is a personal computer or other suitable processing device comprising, for example, a processing unit comprising one or more processors, system memory (volatile and/or non-volatile memory), other non-removable or removable memory (e.g., a hard disk drive, RAM, ROM, EEPROM, CD-ROM, DVD, flash memory, etc.) and a system bus coupling the various computer components to the processing unit. The computing device 22 may also comprise networking capabilities using Ethernet, Wi-Fi, and/or other suitable network format, to enable connection to shared or remote drives, one or more networked computers, or other networked devices. One or more input devices, such as a mouse and a keyboard (not shown) are coupled to the computing device 22 for receiving operator input. A display device (not shown), such as one or more computer screens or monitors, is coupled to the computing device 22 for displaying one or more generated images that are based on ultrasound image data received from the ultrasound imaging system 24 and/or the thermoacoustic image data received from thermoacoustic imaging system 26. The programmed computing device 22 executes program code stored on a computer readable medium and performs methods according to the program code as will be described in more detail below.

[0035]   The ultrasound imaging system 24 comprises an acoustic receiver in the form of an ultrasound transducer 28 that houses one or more ultrasound transducer arrays 30 configured to emit sound waves into the region of interest ROI. Sound waves directed into the region of interest ROI echo off materials within the region of interest ROI, with different materials reflecting varying degrees of sound. Echoes that are received by the one or more ultrasound transducer arrays 30 of the ultrasound transducer 28 are processed by the ultrasound imaging system 24 before being communicated as ultrasound image data to the computing device 22 for further processing and for presentation on the display device as ultrasound images that can be interpreted by an operator. In this embodiment, the ultrasound imaging system 24 utilizes B-mode ultrasound imaging techniques assuming a nominal speed of sound of 1,540 m/s. As ultrasound imaging systems are known in the art, further specifics of the ultrasound imaging system 24 will not be described further herein.

[0036]   The thermoacoustic imaging system 26 comprises an acoustic receiver in the form of a thermoacoustic transducer 32. The thermoacoustic transducer 32 houses one or more thermoacoustic transducer arrays 34 as well as a radio frequency (RF) applicator 36. It will however be appreciated that the RF applicator 36 may be housed separately from the thermoacoustic transducer 32. The RF applicator 36 is configured to emit short pulses of RF energy that are directed into materials within the region of interest ROI. In this embodiment, the RF applicator 36 has a frequency between about 10Mhz and 100GHz and has a pulse duration between about 0.1 nanoseconds and 10 nanoseconds. RF energy pulses delivered to materials within the region of interest ROI heat the materials thereby to induce acoustic pressure waves within the region of interest ROI that are detected by the thermoacoustic transducer 32. Acoustic pressure waves that are detected by the thermoacoustic transducer 32 are processed and communicated as thermoacoustic image data to the computing device 22 for further processing and for presentation on the display device as thermoacoustic

images that can be interpreted by the operator.

[0037] In one potential embodiment, the ultrasound transducer **28** and thermoacoustic transducer **32** are mechanically interconnected so that the spatial relationship between the one or more ultrasound transducer arrays **30**, the one or more thermoacoustic arrays **34** and the RF applicator **36** are known. The spatial relationship is set using a centerline of the one or more ultrasound transducer arrays **30**, the one or more thermoacoustic transducer arrays **34**, and RF applicator **36**. The centerline of the ultrasound transducer array **34** and the thermoacoustic transducer array **34** is defined as being a mid-point of an area of the respective transduce array.

[0038] In this embodiment, the spatial relationship between the one or more ultrasound transducer arrays **30** and the one or more thermoacoustic transducer arrays **34** is such that the centerline of the one or more thermoacoustic transducer arrays **34** is set at a known angle α with respect to the centerline (also known as the axial axis or ultrasound transducer array beam axis) of the one or more ultrasound transducer arrays **30**. The spatial relationship between the one or more thermoacoustic transducer arrays **34** and the RF applicator **36** is such that the centerline of the RF applicator **36** is spaced-apart and generally parallel to the centerline of the one or more thermoacoustic transducer arrays **34.**

[0039] The imaging system **20** utilizes the known spatial relationship between the one or more ultrasound transducer arrays **30** and the one or more thermoacoustic transducer arrays **34** to increase the precision and accuracy of thermoacoustic imaging.

[0040] The coordinate system of the one or more ultrasound transducer arrays **30** of the ultrasound transducer **28** and the coordinate system of the one or more thermoacoustic transducer arrays **34** of the thermoacoustic transducer **32** are mapped by the computing device **22** so that acquired ultrasound and thermoacoustic images can be registered. Alternatively, the thermoacoustic imaging system **26** may make use of the one or more ultrasound transducer arrays **30** of the ultrasound transducer **28** by disconnecting the one or more ultrasound transducer arrays **30** from the ultrasound transducer **28** and connecting the one or more ultrasound transducer arrays **30** to the thermoacoustic transducer **32**. As will be appreciated, by doing this coordinate mapping between the one or more ultrasound transducer arrays **28** and the one or more thermoacoustic transducer arrays **34** is not required.

[0041] Exemplary multi-polar acoustic signals **200**, **205** and **210** are shown in FIG. 2. In this example, the multi-polar acoustic signals **200**, **205** and **210** are generated in response to thermoacoustic imaging of a tissue region of interest ROI comprising a first material **220** and a different type of second material **225** that are separated by a boundary **215**. The dashed line **230** indicates a time point corresponding to the boundary **215**. The differences in the peak-to-peak values of the multi-polar acoustic signals **200**, **205** and **210** represent the extent to which the first material **220** expands into the boundary **215** and into the second material **225** before contracting. As the difference between the amount of energy absorbed of the two different materials at the boundary **215** increases, the amount that the first material **220** expands into the boundary **215** and into the second material **225** increases. As such, the peak-to-peak amplitude of each multi-polar acoustic signal **200**, **205** and **210** is proportional to the difference between the amount of energy absorbed by the two materials **220**, **225**. As can be seen, the peak-to-peak value of multi-polar acoustic signal **200** is greater than that of multi-polar acoustic signals **205**, **210** and the peak-to-peak value of multi-polar acoustic signal **205** is greater than that of multi-polar acoustic signal **210**. As such, the difference between the amount of energy absorbed by the two materials **220, 225** when multi-polar acoustic signal **20**0 is generated is greater than the difference between the amount of energy absorbed by the two materials **220**, **225** when multi-polar acoustic signal **205** is generated. Similarly, the difference between the amount of energy absorbed by the two materials **220**, **225** when multi-polar acoustic signal **205** is generated is greater than the difference between the amount of energy absorbed by the two materials **220**, **225** when multi-polar acoustic signal **210** is generated.

[0042] FIG. 3 shows electric field strength attenuation curves **300, 305** in material **310**, **315** as a function of distance from the RF emitter **112** of a thermoacoustic imaging system. The example is simplified and ignores factors such as reflections off an object boundary. Each electric field strength attenuation curve **300**, **305** represents the electric field strength attenuation of material **310**, **315**, respectively, as a function of distance from the RF applicator **36**. Each electric field strength attenuation curve **300**, **305** corresponds to a material, each of which has a different attenuation coefficient (which could correspond to a different fat concentration for each respective material). The material associated with electric field strength curve **300** has a lower attenuation coefficient than the material associated with electric field strength curve **305**. In one embodiment, the material with a lower attenuation coefficient is has a high fat concentration (e.g. greater than 10%) and the material with a higher attenuation coefficient has a low fat concentration (e.g. less than 10%).

[0043] The material **310** associated with electric field strength attenuation curve **300** has a different Grüneisen parameter than the material **315** associated with electric field strength attenuation curve **305**.

[0044] Different materials (e.g. tissues) have characteristic dielectric properties at a given frequency and a temperature. The dielectric properties of a material determines how much energy is absorbed by the material. An electric field transmitted through the material is attenuated, and the amount of attenuation is determined by both dielectric and physical properties of the material. As an example, compared to normal tissue, fatty tissue absorbs less energy and thus attenuates less electric field. Knowing these properties, the amount of attenuation through a material can be estimated. Furthermore, for a given RF applicator with specific design and tuning, dielectric properties of a material lead to different RF matching

and energy delivery. For example, if the applicator is tuned to match well on human body, it is likely to match poorly to material with high water content, such as ultrasound gel. Therefore, knowing the RF power and matching properties gives information on the material in contact with the applicator.

[0045] FIG. 4 shows the flux (energy gradient) of an RF energy pulse generated by the RF applicator **36**. The RF applicator **36** is located and centered at the 0 value of the x-axis. As can be seen, as the distance from the center of the RF applicator **36** increases, the electric field strength decreases. In other embodiments, actual E-field distribution can have more complex shapes, depending on the modeled object.

[0046] Turning now to FIG. 5, a method for determining at least one parameter of interest of a material is shown and is generally identified by reference numeral **500**. Initially during the method, a reference and a material having at least one parameter of interest are positioned adjacent to one another within a region of interest ROI (step **510**). In this embodiment, the region of interest ROI is *in vitro.*

[0047] In an embodiment that is outside of a human body, the reference can be in the form of a pad and is made of a known material, such as for example rubber. Other examples of pad construction can include but are not limited to gels made of materials such as agar, gelatin, gelwax, or the like. The pad should have known dielectric properties, low acoustic attenuation properties, minimal RF interference properties, and good acoustic matching properties. The reference or pad is over top of the material of interest.

[0048] At the boundary **126** and **144,** multi-polar acoustic signals are generated that are detected and received by the thermoacoustic transducer 32 (step **520**).

[0049] The multi-polar acoustic signals received by thermoacoustic transducer **32** are communicated as thermoacoustic data to the computing device **22** for processing (step **530**). In this embodiment, the computing device **22** is programmed to process the multi-polar acoustic signals to determine an electric field strength at the boundary.

[0050] The thermoacoustic pressure $p(\underline{r}, t)$ produced by a heat source $H(\underline{r}, t)$ obeys the following equation:

$$\nabla^2 p(\underline{r}, t) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} p(\underline{r}, t) = -\frac{\beta}{C_p}\frac{\partial}{\partial t} H(\underline{r}, t) \qquad (1)$$

where $\underline{r}$ is the spatial position vector, β is the isobaric volume expansion coefficient, c is the sound speed and C_p is the specific heat capacity. Solving equation 1 with respect to the acoustic pressure wave $p(\underline{r}, t)$ yields the following forward problem:

$$p(\underline{r}, t) = \frac{\beta}{4\pi C_p}\iiint \frac{\partial \underline{r}}{|\underline{r}-\underline{r}'|}\frac{\partial H(\underline{r}', t')}{\partial t'}\Big|_{t'=t-\frac{r'}{c}} \qquad (2)$$

[0051] The heat source $H(\underline{r}, t)$ is modeled as the product of two factors, which are the spatial distribution of energy absorption $A(\underline{r})$ and the temporal irradiation function $I(t)$. The spatial distribution of energy absorption $A(\underline{r})$ is determined based on characteristics of the materials(s) being imaged. Since the thermoacoustic transducer array 30 has a finite bandwidth, received thermoacoustic data $p_d(\underline{r}, t)$ is a result of the convolution of acoustic pressure wave $p(\underline{r}, t)$ and the impulse response of the thermoacoustic transducer array 30 $h(t)$ as set out in equation 3:

$$p_d(\underline{r}, t)= p(\underline{r}, t) *_t h(t) \qquad (3)$$

where *t denotes a one-dimensional temporal convolution.

[0052] As will be appreciated, for conventional thermoacoustic imaging, the goal is to recover the spatial absorption distribution $A(r)$ by inverting the forward problem. As such, the irradiation function is modeled as a temporal function that is uniform at a given time point.

[0053] Due to the limited bandwidth of the thermoacoustic transducer array 30, accurately recovering the absorption distribution is not trivial. As such, extracting quantitative information requires sophisticated methods beyond that of conventional reconstruction methods.

[0054] When the material having the parameter of interest is heated with a pulse of RF energy, the power deposition per unit volume $A(\underline{r})$ is expressed as:

$$A(\underline{r}) = \omega \varepsilon_0 \varepsilon_r'' E^2(\underline{r}) \qquad (4)$$

where ω is the radian frequency, ε_0 is the vacuum permittivity, $\varepsilon_r^{''}$ is the imaginary part of the relative permittivity (also referred to as the conductivity) of the material having the parameter of interest and $E(\underline{r})$ is the electric field strength. The strength of thermoacoustic data $S(\underline{r})$ obtained from the material having the parameter of interest is the product of the deposited energy and the Grüneisen parameter of the tissue Γ:

$$S(\underline{r}) = \Gamma A(\underline{r}) = \Gamma \omega \varepsilon_0 \varepsilon_r^{''} E^2(\underline{r}) \qquad (5)$$

[0055]   Within a dielectric lossy medium, the electric field strength is attenuated as it propagates through the medium. The amount of attenuation is determined by various factors such as for example characteristics of region of interest and characteristics of the RF applicator **36**. The spatial distribution of the electric field is:

$$E(\underline{r}) = E_0 E_A(\underline{r}) \qquad (6)$$

where E_0 is the maximum electric field strength of the region of interest and $E_A(\underline{r})$ is the attenuation of the electric field over a given space. For a simple 1D case, the attenuation $E_A(\underline{r})$ can be expressed in exponential form:

$$E_A(d) = e^{-\eta d} \qquad (7)$$

where η is the electric field absorption coefficient of the region of interest and d is the distance of the region of interest from the RF applicator **36**.

[0056]   In this embodiment, equation 5 is used as a model to infer material parameters from the thermoacoustic data. As mentioned, thermoacoustic data obtained from the region of interest is in the form of multi-polar acoustic signals. The strength or peak-to-peak amplitudes of the multi-polar acoustic signals represent the absorption property difference between the material having the parameter of interest and the reference. Further, the phase of the thermoacoustic data at the boundary indicates which material (the material having the parameter of interest or the reference) has a higher or lower absorption coefficient. The strength or peak-to-peak amplitudes S_l of each multi-polar acoustic signal measured at the boundary location, r, is expressed in equation 8:

$$S_l = (\Gamma_{MOI} \varepsilon_{r,MOI}^{''} - \Gamma_{ref} \varepsilon_{r,ref}^{''}) \omega \varepsilon_0 E_l^{2} \qquad (8)$$

where MOI denotes the material having the parameter of interest, ref denotes the reference, and E_l denotes the incident electric field strength at the boundary.

[0057]   As shown in equation 8, the strength of the multi-polar acoustic signal is determined by material parameters and the strength of the electric field at the boundary.

[0058]   Using equation 6, the incident electric field E_l at a boundary location (going from the reference to the material having the parameter of interest) can be estimated as:

$$E_l = E_0 e^{-n_{ref} d_{ref}} \qquad (9)$$

where E_0 is the electric field strength at the start of the reference, n_{ref} is the attenuation coefficient of the reference, and d_{ref} is a thickness of the reference. As will be appreciated, the electric field strength E_0 may be modeled using a finite-difference time domain (FDTD method) or may be inferred from measurements taken at the RF applicator 36. The electric field strength E_0 may alternatively be directly measured at the boundary using an electric field probe.

[0059]   The multi-polar acoustic signal strength at a boundary location can be derived from equations 8 and 9:

$$S_l = (\Gamma_{MOI} \varepsilon_{r,MOI}^{''} - \Gamma_{ref} \varepsilon_{r,ref}^{''}) \omega \varepsilon_0 E_l^{2}$$
$$= (\Gamma_{MOI} \varepsilon_{r,MOI}^{''} - \Gamma_{ref} \varepsilon_{r,ref}^{''}) \omega \varepsilon_0 (E_0 e^{-n_{ref} d_{ref}})^2 \qquad (10)$$

[0060] Equation 10 can be deduced to:

$$\Gamma_{MOI}\varepsilon_{r,MOI}^{''} = \frac{S_l}{\omega\varepsilon_0(E_0 e^{-n_{ref}d_{ref}})^2} + \Gamma_{ref}\varepsilon_0\varepsilon_{r,ref}^{''} \qquad (11.1)$$

[0061] Radio frequency (RF) characteristics are used to determine the parameter of interest of the material. In this embodiment, a Voltage Standing Wave Ratio (VSWR) is calculated (step **540**) and is a measure of how efficiently RF power is being transmitted from the RF applicator. Generally, the VSWR is calculated by monitoring the RF forward and reflected power of the RF energy pulses. The RF forward power is the power of the RF energy pulses emitted by the RF applicator. The RF reflected power is the power of the RF energy pulses that are reflected back to the RF applicator. Using the RF forward and reflected powers, the voltage standing wave ratio (VSWR) is calculated.

[0062] As mentioned previously, during step **520**, RF energy pulses are directed into the region of interest that comprises the material having the parameter of interest. The RF energy pulses have a known frequency and a known amplitude. In this embodiment, a first power monitor is used to measure the forward power of the RF energy pulses. A second power monitor is used to measure the reflected power of the RF energy pulses.

[0063] The VSWR is calculated as a ratio of the measured forward power and the measured reflected power.

[0064] In one example, a user analyzes a liver tissue sample with unknown fat content. If the reference layer is not too thick, the property of that liver would affect the matching of the applicator to the object (reference/liver tissue). The VSWR value of the sample may not be sensitive enough to determine what the fat content of the liver is. However, the VSWR value can be widely different from having a different object under the reference. VSWR can be affected by both the identity of the object and its property. It may not be the dominating factor in the decision regarding an object, but knowledge of the VSWR still has value.

[0065] At least one parameter of interest of the material is determined using the determined electric field strength and the calculated VSWR (step **550**). In this embodiment, the parameter of interest of the material may be at least one of conductivity ($\varepsilon_r^{''}$) (S/m), Grüneisen parameter (Γ), specific heat capacity (γ) and/or a parameter k_{MOI}.

[0066] The conductivity ($\varepsilon_r^{''}$) of the material may be calculated using thermoacoustic signal strength and the Gruneisen parameter (Γ).

[0067] The Gruneisen parameter (Γ) of the material may be calculated using the thermoacoustic signal strength and the conductivity ($\varepsilon_r^{''}$) of the material.

[0068] Specific heat capacity (γ) is calculated using known equations, such as the one shown below as equation 12.

$$\gamma = \frac{\alpha K_T}{\rho C_V} = \frac{\alpha K_S}{\rho C_P} = \frac{\alpha v_s^2}{C_P} \qquad (12)$$

where C_P and C_V are the principal (i.e. per-mass) heat capacities at constant pressure and volume, α is the volume thermal expansion coefficient, K_S and K_T are the adiabatic and isothermal bulk moduli, v_s is the speed of sound in the medium, and ρ is density.

[0069] The parameter k_{MOI} represents how much thermoacoustic signal will be generated for a given amount of energy. It is the multiplication of (energy absorption) and (absorbed energy conversion to acoustic signal). The parameter k_{MOI} is calculated by solving the following equation:

$$k_{MOI} = \Gamma_{MOI}\varepsilon_{r,MOI}^{''} = \frac{S_l}{\omega\varepsilon_0(E_0 e^{-n_{ref}d_{ref}})^2} + \Gamma_{ref}\varepsilon_0\varepsilon_{r,ref}^{''} \qquad (11.2)$$

[0070] Table 1 summarizes the measurements required to determine a particular parameter of interest:

Table 1: Lookup Table to Determine Parameter of Interest of an Unknown Material

Parameter to be determined	Required Measurements	Relevant equation
Conductivity ($\varepsilon_r^{''}$) (S/m)	- Thermoacoustic signal strength - Grüneisen parameter (Γ)	11.1

(continued)

Parameter to be determined	Required Measurements	Relevant equation
Grüneisen parameter (Γ)	- Thermoacoustic signal strength - Conductivity (ε_r'')	11.1
Specific heat capacity (γ)	- Thermoacoustic signal strength - conductivity (ε_r'') - speed of sound - volume thermal expansion coefficient - adiabatic or isothermal bulk moduli - density - mass	12
Parameter k_{MOI}	- conductivity (ε_r'') - Grüneisen parameter (Γ)	11.2

[0071]   Although during method **500** the identity of the material having the parameter of interest is known, at least one parameter of interest may be determined if the identity of the material is unknown. In this embodiment, Table 2 is used to determine at least one parameter of interest of an unknown material:

Table 2: Lookup Table to Determine Parameter of Interest of an Unknown Material

Measurements			Material at condition 1	Material at condition 2
Quantitative	Thermoacoustic	Material independent characteristic TA signal		
		Corrected TA signal at the reference to material boundary		
		Characteristic TA property (Gruneisen x Conductivity)		
	Power measurements (no reference)	Forward		
		Transmitted		
		VSWR		
	Power measurements (with reference)	Forward		
		Transmitted		
		VSWR		
	Combined metrics	Ratio between TA signals		
		Function of ratio between TA signals and TA properties		
		Function of TA signal, properties, and power measurements		
	Ultrasound	Speed of sound		
Semi-quantitative	Ultrasound	Scattering		

(continued)

Measurements			Material at condition 1	Material at condition 2
Other characteristics	Color			
	Transparency			
	Texture			
	Material state			
	Odor			

[0072] Experiments and/or modeling will be utilized to generate the data for Table 2 at selected condition(s). For a material with unknown property, various measurements can be made at different condition(s) and compared against the lookup table. Then, a parameter can be determined at the different condition(s) by estimating the effect that the change in condition(s) (selected condition(s) versus different condition(s)) has upon the parameter.

[0073] Semi-quantitative measurements may be used to help determine the parameter of interest. For example, for a material with an unknown condition, each quantitative property (e.g. parameter of interest) may be compared against conditions listed in Table 2. An exemplary comparison metric is shown in equation 13:

$$ Q_i \;=\; \sum_{j=1}^{N} \;\; (p^j_{\,i} - p^j_{\,unknown})w^j \qquad\qquad (13) $$

where N is the total number of quantitative property being included in the comparison, i denotes the ith condition in the lookup table, j denotes j^{th} material property, p^j_i denotes the jth property of material with i^{th} condition $p^j_{unknown}$ denotes the jth property of the material with unknown condition, w^j denotes a weighting factor for j^{th} property. Material with the lowest Q_i will be considered as the identified condition of the material. As will be appreciated, only part of the materials properties may be used to determine the material condition.

[0074] In some embodiments, the identity of the material will not be directly selected from the lookup table, but the likelihood of its identity will be suggested based on the acquired metrics. For example, a material may have 60% likelihood to be material 1 and 40% likelihood to be material 2.

[0075] Those skilled in the art will appreciate that the at least one parameter of interest may be used to help identify the material using a lookup table generated from previously performed models and experiments. Table 3 illustrates an exemplary lookup table:

Table 3: Grüneisen Parameter and Conductivity of Materials at Room Temperature (at 434 MHz)

	Distilled Water	Subcutaneous fat	Muscle	Blood	Mineral Oil
Grüneisen parameter (Γ)	0.11	0.81	0.21	0.14	0.71
Conductivity ($\varepsilon_r^{''}$) (S/m)	0.045	0.042	0.8	1.36	0
Parameter (k)	0.00495	0.03402	0.168	0.1904	0

[0076] Those skilled in the art will appreciate that other parameters of interest of the material may be determined. For example, a lookup table comprising physical characteristics of the material may be used. Table 4 illustrates an exemplary lookup table:

Table 4: Physical Characteristics of Materials

	Distilled water	Fat	Mineral oil	Concrete
Color	colorless	white	colorless	white/gray/color ed
Transparency	transparent	opaque	transparent	opaque
Odor	odorless	rancid	odorless	concrete odor
texture	smooth	smooth	smooth	rough

(continued)

	Distilled water	Fat	Mineral oil	Concrete
material state	liquid	solid	liquid	solid

[0077] Those skilled in the art will appreciate that the ultrasound imaging system may be used to determine at least one parameter of interest of the material. For example, the speed of sound and scattering properties of the material can be observed and compared to the speed of sound and scattering properties of the reference. The ultrasound imaging system may also be used to inspect a condition of the material and to check for undesirable structures such as for example cracks or air bubbles that may interfere with the thermoacoustic imaging process.

[0078] Those skilled in the art will appreciate that the phase of the multi-polar acoustic signals may be used to help identify at least one parameter of interest of the material. Since the reference is made of a known material, the material that absorbs more energy than the other material expands rapidly across the boundary and into the other material, that expands less, and then quickly contract. The phase of the multi-polar acoustic signal depends on which one of the materials absorbs more energy.

[0079] Those skilled in the art will appreciate that the strength or peak-to-peak values of the multi-polar acoustic signals may be used to help identify at least one parameter of interest of the material. Since the reference is made of a known material with a known absorption property and the strength or peak-to-peak values of the multi-polar acoustic signals depend on the relative absorption properties of the materials, the absorption property of the material can be deduced.

[0080] Although the reference is described as being in the form of a pad made of a known material and is placed on top of the material, those skilled in the art will appreciate that alternatives are available. For example, in another embodiment the reference may be in the form of a container or petri dish configured to hold or contain the material of interest.

[0081] In one embodiment, the pad is flexible. For example, the pad can be flexible enough to provide good contact with a cylindrical object.

[0082] Turning now to FIG. 6, another embodiment of a method for identifying a material of interest is shown and is generally identified by reference numeral **700**. Method **700** is generally identical to that of method **500** with the following exceptions. During method **700**, rather than the region of interest being *in vitro,* in method **700** region of interest is *in vivo.* As such, initially during the method, a region of interest ROI that contains a material having a parameter of interest and a reference are located within a subject's body (step **510**). In this embodiment, the region of interest ROI is located using the ultrasound imaging system **24**. Specifically, ultrasound image data obtained by the ultrasound imaging system **24** is communicated to the computing device **22**. The ultrasound image data is processed by the computing device **22** and a reconstructed ultrasound image is presented on the display device. The operator moves the ultrasound transducer **28** until the region of interest is located. When locating the region of interest, the computing device **22** overlays information associated with the angle of the centerline of the one or more transducer arrays 30 of the ultrasound transducer **28** overtop of the reconstructed ultrasound image on the display device. The information is used to provide feedback to the operator to ensure the axial axis of the ultrasound transducer **28** is generally perpendicular to a boundary between the material and the reference.

[0083] Once the region of interest ROI has been located, at least one boundary between the material having the parameter of interest and the reference is identified (step **715**). In this embodiment, one boundary location is identified and this is done using ultrasound images generated by the ultrasound imaging system. The boundary location is identified by the operator using an input device such as a mouse coupled to the computing device **22.**

[0084] Once the boundary has been identified, steps **720**, **730**, **740** and **750** of method **700** are generally identical to that of steps **520**, **530**, **540** and **550** of method **500**, respectively.

[0085] Those skilled in the art will appreciate that in some embodiments the thermoacoustic data may need to be corrected. For example, the shape of the boundary may be deformed. In this embodiment, the shape and/or angle of the boundary may be estimated using the ultrasound imaging system and known image processing techniques.

[0086] In this embodiment, received signals at the thermoacoustic transducer array may be expressed using equation 14:

$$p_s(t) = \int_S \quad p(\underline{r}, t) dS \qquad (14)$$

where S is the surface area of the thermoacoustic transducer array. As will be appreciated, the properties of the thermoacoustic transducer array and its positioning relative to the region of interest change the characteristics of the thermoacoustic data. The multi-polar acoustic signals received by the thermoacoustic transducer array are affected by various factors that are not related to signal generation by rather associated with signal propagation. These factors

depend on transducer spatial sensitivity, relative positioning between the thermoacoustic transducer array and the boundary between the material and the reference, and the relative shape of the reference with respect to the thermoacoustic transducer array surface. Even for the same region of interest and the same thermoacoustic transducer array, changing the position and angle of the thermoacoustic transducer array during thermoacoustic data acquisition results in different measurements.

[0087]   In this embodiment, a compensation factor is calculated based on information and measurements provided by the operator or estimated using acquired ultrasound image data. The compensation factor may be a single factor or multiple factors, where each factor is calculated information such as size and shape of the reference and the angle between the ultrasound transducer array and the boundary. In one embodiment, the compensation factors are calculated based on theoretical methods such as by using acoustic propagation and ultrasound transducer properties. In another embodiment, the compensation factors may be obtained from phantom and clinical studies. In yet another embodiment, both theoretical and experimental methods may be used.

[0088]   When the thermoacoustic data is adjusted with the compensator factor, the thermoacoustic signal strength, S_l, in equation 12 is replaced by the adjusted thermoacoustic signal strength, $\underline{S_l}$:

$$k_{MOI} = \Gamma_{MOI}\varepsilon_{r,MOI}^{''} = \frac{\underline{S_l}}{\omega\varepsilon_0(E_0 e^{-n_{ref}d_{ref}})^2} + \Gamma_{ref}\varepsilon_0\varepsilon_{r,ref}^{''} \quad (15)$$

[0089]   In this, when the material having the parameter of interest is large enough to ignore the partial volume effect, only the angle based adjustment is required. When a tangent vector of the material at the boundary and the centerline of the one or more transducer arrays 34 is not perpendicular, signal adjustment is made to the acquired measurement. This adjustment is expressed as:

$$\underline{S_l} = S_l C(\theta) \quad (16)$$

where C is an angle based adjustment factor, θ is the angle between the tangent vector of the material at the boundary and the centerline of the one or more transducer arrays 34.

[0090]   In some embodiments, various measurements from thermoacoustic data can be used to construct a parameter, which may be tabulated and used to help identify the material. For example, thermoacoustic data having no object related signals may be obtained at the beginning of the measurements. For example, thermoacoustic data may be obtained with the coupling medium (e.g., ultrasound gel) being present, thermoacoustic data may be obtained and may comprise signals generated from internal components or transducer components, the boundary between the reference and the RF applicator, the internal components of the RF applicator, or other parts of the RF applicator. Thermoacoustic data from such sources are independent of the material and can be used to compensate or normalize the thermoacoustic signal from the material. A simple ratio between thermoacoustic data obtained at the reference to the boundary and thermoacoustic data having no object related signals may be used as a metric. As will be appreciated, various combinations of thermoacoustic data having no object related signals may be obtained.

[0091]   Those skilled in the art will appreciate that in embodiments, the boundary between the reference and the material may be automatically defined using algorithms based on ultrasound segmentation or thermoacoustic data analysis. As will be appreciated, both operator-defined and automatic methods may be combined.

[0092]   Although in embodiments a single boundary, a single material and a single reference are imaged, those skilled in the art will appreciate that alternatives are available. An example is shown in FIG. 8. In this embodiment, a user utilizes the computing device 22 to operate the ultrasound imaging system 24. The ultrasound imaging system 24 sends a signal to the one or more ultrasound transducer arrays 30, which sends sound waves 120 into reference 142 which is in the form of a pad made of a known material and is positioned within the region of interest 116. Within the region of interest 116, there is a first boundary 126 at first boundary locations 134 and 136, a first material 128, a second material 146, and a second boundary 144 at second boundary locations 148 and 150. The ultrasound transducer arrays 30 receive reflected sound waves to generate a B-mode image via the ultrasound imaging system 24. The extent of the B-mode image is conical in shape and is shown with B-mode image limits 118. The B-mode image gives the physical location of boundary 126, enabling the computing device 22 to correlate obtained data from the thermoacoustic transducer array 34 and RF emitter 36. Once position coordinates are known, the ultrasound imaging system 24 is turned off to eliminate potential interference with the thermoacoustic imaging system 26. The thermoacoustic imaging system then initiates the RF emitter 36 to send RF energy pulses 122 into reference 142. The RF energy 122 pulses are absorbed in the region of interest 116. The difference between RF energy absorbed in the reference 142 and the first material 128 creates multi-polar acoustic signals 124 and 138 emanating from boundary locations 134 and 136. In addition, the difference between RF energy absorbed in the first material 128 and the second material 146 creates multi-polar acoustic signals

152 and **154** emanating from boundary locations **148** and **150**. The known parameters of the reference **142** can then be used in conjunction with thermoacoustic data from the multi-polar acoustic signals generated at boundary locations **134** and **136** to determine at least one parameter of the first material **128**. Additionally, the at least one parameter of interest of the first material **128** can be used in conjunction with thermoacoustic data from the multi-polar acoustic signals generated at boundary locations **148** and **150** to determine at least one parameter of interest of the second material **146.**

[0093] Although in embodiments described above the one or more ultrasound transducer arrays are described as being disconnectable from the ultrasound imaging system and reconnectable to the thermoacoustic imaging system, those skilled in the art will appreciate that alternatives are available. For example, the one or more ultrasound transducer arrays may be connected to a hub which itself is connected to the ultrasound imaging system and the thermoacoustic imaging system. In this embodiment, the hub may be controlled by the computing device or by other input to switch operation between the ultrasound imaging system and the thermoacoustic imaging system and vice versa.

[0094] Although in embodiments described above a metric used to estimate the signal strength at the boundary is the difference between two or more peaks of a multipolar signal, those skilled in the art will appreciate that the metric may be a simple peak (maximum), a p-norm, area under the multipolar signal, etc.

[0095] As will be appreciated, embodiments of image processing described above can be performed on ultrasound and thermoacoustic images in real-time or off-line using images stored in memory.

[0096] Although the thermoacoustic imaging system is described as comprising an RF applicator configured to generate short pulses of RF electromagnetic radiation, those skilled in the art will appreciate that in other embodiments the thermoacoustic imaging system may comprise a visible light source or an infrared radiation source with a wavelength between 400nm and 10μm and a pulse duration between 10 picoseconds and 10 microseconds.

[0097] Although in embodiments described above the thermoacoustic imaging system and the ultrasound imaging system are described as using one or more ultrasound transducer arrays, those skilled in the art will appreciate that the alternatives are available. For example, a single transducer element, an ultrasound transducer array having a linear or curved one-dimensional array, or a two-dimensional ultrasound transducer array may be used.

[0098] Although in embodiments described above, thermoacoustic data is obtained of a single region of interest, those skilled in the art will appreciate that multiple regions of interest may be analyzed and combined.

[0099] Those skilled in the art will appreciate that the above-described ultrasound image data and thermoacoustic data may be one-dimensional, two-dimensional or three-dimensional. In embodiments, the ultrasound image data may be in a different dimension than the thermoacoustic data. For example, ultrasound image data may be two-dimensional and the thermoacoustic data may be one-dimensional. Further, different fields of view may be used.

[0100] In another embodiment, different types or models of transducer arrays may be used with the thermoacoustic and ultrasound imaging systems. In this embodiment, a transform may be used to map a thermoacoustic absorption data to the ultrasound image. In another embodiment, in the event that knowledge of transducer array geometry is not readily available, the thermoacoustic absorption data may be mapped to the ultrasound image using a phantom with reference points. In this embodiment, a transform may be used to map known phantom reference points from the thermoacoustic absorption data to the phantom reference points on the ultrasound image.

[0101] Although the ultrasound imaging system is described as using B-mode ultrasound imaging techniques, other techniques may be used such as for example power Doppler images, continuous wave Doppler images, strain imaging, etc.

[0102] Although in embodiments described above thermoacoustic data is obtained of the region of interest, those skilled in the art will appreciate that thermoacoustic data may be obtained for an area larger than the region of interest.

[0103] As described above, the programmed computing device executes computer program code stored on at least one computer readable medium. The computer readable medium may be memory devices or transmitting devices, thereby making a computer program product or article of manufacture according to the invention. As such, functionality may be imparted on a physical device as a computer program existent as instructions on any computer-readable medium such as on any memory device or in any transmitting device, that are to be executed by a processor.

[0104] Examples of memory devices include, hard disk drives, diskettes, optical disks, magnetic tape, semiconductor memories such as FLASH, RAM, ROM, PROMS, and the like. Examples of networks include, but are not limited to, the Internet, intranets, telephone/modem-based network communication, hard-wired/cabled communication network, cellular communication, radio wave communication, satellite communication, and other stationary or mobile network systems/communication links.

[0105] A machine embodying the invention may additionally or alternatively include one or more processing systems including, for example, computer processing unit (CPU) or processor, memory/storage devices, communication links, communication/transmitting devices, servers, I/O devices, or any subcomponents or individual parts of one or more processing systems, including software, firmware, hardware, or any combination or subcombination thereof.

[0106] Using the description provided herein, embodiments described above may be implemented as a machine, process, or article of manufacture by using standard programming and/or engineering techniques to produce programming software, firmware, hardware or any combination thereof.

[0107] Using the description provided herein, those skilled in the art will be readily able to combine software created as described with appropriate or special purpose computer hardware to create a computer system and/or computer subcomponents embodying the invention, and to create a computer system and/or computer subcomponents for carrying out at least some steps of the methods described herein.

[0108] Those skilled in the art will appreciate that in embodiments the computing device may be programmed to adjust parameters of the RF applicator.

[0109] Those skilled in the art will appreciate that the above-described method may be performed on a phantom designed to mimic an area of interest. In this embodiment, the RF applicator may be adjusted to maximize the peak-to-peak amplitudes of the multi-polar acoustic signals prior to imaging a material. Further, the method may be performed on numerous phantoms of various properties to mimic different materials.

[0110] Although embodiments have been described above with reference to the accompanying drawings, those of skill in the art will appreciate that variations and modifications may be made without departing from the scope thereof as defined by the appended claims.

Claims

1. A method for determining at least one parameter of interest of a material, the method comprising:

   directing, using a radio frequency (RF) applicator, one or more RF energy pulses into a region of interest, the region of interest comprising a material having a parameter of interest and at least one reference, the material and the reference separated by at least one boundary;
   detecting, using an acoustic receiver, at least one multi-polar acoustic signal generated in the region of interest in response to the RF energy pulses, wherein the at least one multi-polar acoustic signal is an acoustic pressure wave;
   processing the at least one multi-polar acoustic signal to determine an electric field strength at the boundary;
   calculating a voltage standing wave ratio (VSWR) of the one or more RF energy pulses;
   monitoring a forward power and a reflected power of the one or more RF energy pulses to calculate the VSWR; and
   determining the at least one parameter of interest of the material based at least on the determined electric field strength and the VSWR.

2. The method of claim 1 wherein the at least one parameter of interest is one of a Grüneisen Parameter of the material and a conductivity of the material.

3. The method of claim 2, wherein the at least one parameter of interest is a product of the Grüneisen Parameter of the material and the conductivity of the material.

4. The method of claim 2 wherein the at least one parameter of interest is a specific heat capacity of the material.

5. The method of claim 1, wherein an identity of the material is known.

6. The method of claim 5, wherein the determining comprises estimating the at least on parameter of interest.

7. The method of claim 1, wherein an identity of the material is unknown.

8. The method of claim 7, wherein the determining comprises looking up the at least one parameter of interest in a lookup table.

9. The method of claim 1, wherein the electric field strength is determined based on an input power of the RF applicator and an attenuation coefficient of the reference.

10. The method of claim 1, wherein the electric field strength is determined based on an estimated thickness of the reference and an attenuation coefficient of the reference.

11. The method of claim 1 wherein each multi-polar acoustic signal corresponds to a separate boundary location.

12. The method of claim 1, wherein detecting the at least one multi-polar acoustic signal is achieved using a thermoa-

coustic imaging system.

13. A system for determining at least one parameter of interest of a material, the system comprising:

a reference;
a thermoacoustic imaging system (26) comprising a radio frequency (RF) applicator (36) configured to emit RF energy pulses into the region of interest comprising a material having at least one parameter of interest and a reference, the material and the reference separated by at least one boundary,
an acoustic receiver (28) configured to receive at least one multi-polar acoustic signal generated in the region of interest in response to the RF energy pulses, wherein the at least one multi-polar acoustic signal is an acoustic pressure wave;
a first power monitor for measuring the forward power of the RF energy pulses;
a second power monitor for measuring the reflected power of the RF energy pulses; and
one or more processors (22) configured to:

process multi-polar acoustic signals received by the acoustic receiver to determine an electric field strength at the boundary;
calculate a voltage standing wave ratio (VSWR) of the one or more RF energy pulses;
monitor a forward power and a reflected power of the one or more RF energy pulses to calculate the VSWR; and
determine the at least one parameter of interest of the material based at least on the determined electric field strength and the VSWR.

14. The system of claim 13 wherein the at least one parameter of interest is one of a Grüneisen Parameter of the material and a conductivity of the material.

15. The system of claim 14 wherein the at least one parameter of interest is a product of the Grüneisen Parameter of the material and the conductivity of the material.

16. The system of claim 14 wherein the at least one parameter of interest is a specific heat capacity of the material.

17. The system of claim 13 further comprising at least one power monitor configured to monitor a forward and reflected power of the RF energy pulses, and the one or more processors are configured to calculate the VSWR using the forward and reflected power of the RF energy pulses.

18. The system of claim 13 wherein the electric field strength is determined based on an input power of the RF applicator and an attenuation coefficient of the reference.

19. A non-transitory computer readable medium having stored thereon computer program code executable by one or more processors and causing the system of any of claims 13 to 18 to perform the steps of any of claims 1 to 12.

Patentansprüche

1. Ein Verfahren zum Bestimmen von mindestens einem interessierenden Parameter eines Materials, wobei das Verfahren umfasst: Richten eines oder mehrerer HF-Energieimpulse in einen Bereich von Interesse unter Verwendung eines Hochfrequenzapplikators (RF), wobei der Bereich von Interesse ein Material mit einem Parameter von Interesse und mindestens eine Referenz umfasst, wobei das Material und die Referenz durch mindestens eine Grenze getrennt sind;

Erfassen von mindestens einem mehrpolaren akustischen Signal, das in Reaktion auf die HF-Energieimpulse in der interessierenden Region erzeugt wird, unter Verwendung eines akustischen Empfängers;
Verarbeiten des mindestens einen multipolaren akustischen Signals, um eine elektrische Feldstärke an der Grenze zu bestimmen;
Berechnen eines Stehwellenverhältnisses (VSWR) der einen oder mehreren HF-Energieimpulse;
Überwachen einer Vorwärtsleistung und einer reflektierten Leistung des einen oder der mehreren HF-Energieimpulse, um das VSWR zu berechnen, und
Bestimmen des mindestens einen interessierenden Parameters des Materials zumindest basierend auf der

bestimmten elektrischen Feldstärke und dem VSWR.

2. Die Methode der Anspruch 1, wobei der mindestens eine Parameter von Interesse ein Grüneisen-Parameter des Materials oder eine Leitfähigkeit des Materials ist.

3. Die Methode der Anspruch 2, wobei der mindestens eine Parameter von Interesse ein Produkt aus dem Grüneisen-Parameter des Materials und der Leitfähigkeit des Materials ist.

4. Die Methode der Anspruch 2, wobei der mindestens eine Parameter von Interesse eine spezifische Wärmekapazität des Materials ist.

5. Die Methode der Anspruch 1, wobei die Identität des Materials bekannt ist.

6. Die Methode der Anspruch 5, , wobei das Bestimmen das Schätzen des mindestens einen interessierenden Parameters umfasst.

7. Die Methode der Anspruch 1, wobei die Identität des Materials unbekannt ist.

8. Die Methode der Anspruch 7, wobei das Bestimmen das Nachschlagen des mindestens einen interessierenden Parameters in einer Nachschlagetabelle umfasst.

9. Die Methode der Anspruch 1, wobei die elektrische Feldstärke basierend auf einer Eingangsleistung des HF-Applikators und einem Dämpfungskoeffizienten der Referenz bestimmt wird.

10. Die Methode der Anspruch 1, wobei die elektrische Feldstärke basierend auf einer geschätzten Dicke der Referenz und einem Dämpfungskoeffizienten der Referenz bestimmt wird.

11. Die Methode der Anspruch 1, wobei jedes mehrpolare akustische Signal einer separaten Grenzstelle entspricht.

12. Die Methode der Anspruch 1, wobei das Erfassen des mindestens einen multipolaren akustischen Signals unter Verwendung eines thermoakustischen Bildgebungssystems erfolgt.

13. System zur Bestimmung mindestens eines interessierenden Parameters eines Materials, wobei das System eine Referenz umfasst; ein thermoakustisches Abbildungssystem (26), das einen Hochfrequenz (HF)-Applikator (36) umfasst, der so konfiguriert ist, dass er HF-Energieimpulse in den interessierenden Bereich emittiert, der ein Material mit mindestens einem interessierenden Parameter und eine Referenz umfasst, wobei das Material und die Referenz durch mindestens eine Grenze getrennt sind, einen akustischen Empfänger (28), der so konfiguriert ist, dass er mindestens ein multipolares akustisches Signal empfängt, das in dem interessierenden Bereich in Reaktion auf die HF-Energieimpulse erzeugt wird, wobei das mindestens eine multipolare akustische Signal eine akustische Druckwelle ist;

einen ersten Leistungsmonitor zur Messung der Vorwärtsleistung der HF-Energieimpulse; einen zweiten Leistungsmonitor zur Messung der reflektierten Leistung der HF-Energieimpulse; und
einen oder mehrere Prozessoren (22), die dafür konfiguriert sind:

Multipolare akustische Signale zu verarbeiten, die von dem akustischen Empfänger empfangen werden, um eine elektrische Feldstärke an der Grenze zu bestimmen;
ein Spannungs-Stehwellen-Verhältnis (VSWR) des einen oder der mehreren HF-Energieimpulse zu berechnen;
eine Vorwärtsleistung und eine reflektierte Leistung des einen oder der mehreren HF-Energieimpulse zu überwachen, um das VSWR zu berechnen; und
Bestimmen des mindestens einen interessierenden Parameters des Materials zumindest auf der Grundlage der bestimmten elektrischen Feldstärke und des VSWR.

14. Das System der Anspruch 13, wobei der mindestens eine Parameter von Interesse ein Grüneisen-Parameter des Materials oder eine Leitfähigkeit des Materials ist.

15. Das System der Anspruch 14, wobei der mindestens eine Parameter von Interesse ein Produkt aus dem Grüneisen-Parameter des Materials und der Leitfähigkeit des Materials ist.

16. Das System der Anspruch 14, wobei der mindestens eine Parameter von Interesse eine spezifische Wärmekapazität des Materials ist.

17. Das System der Anspruch 13, weiterhin umfassend mindestens einen Leistungsmonitor, der konfiguriert ist, um eine Vorwärts- und eine reflektierte Leistung der HF-Energieimpulse zu überwachen, und wobei der eine oder die mehreren Prozessoren konfiguriert sind, um das VSWR unter Verwendung der Vorwärts- und der reflektierten Leistung der HF-Energieimpulse zu berechnen.

18. Das System der Anspruch 13, wobei die elektrische Feldstärke basierend auf einer Eingangsleistung des HF-Applikators und einem Dämpfungskoeffizienten der Referenz bestimmt wird.

19. Ein nicht-übertragbares computerlesbares Medium, auf dem ein Computerprogramm gespeichert ist, das von einem oder mehreren Prozessoren ausgeführt werden kann und das System nach einem der Ansprüche 13 bis 18 veranlasst, die Schritte nach einem der Ansprüche 1 bis 12 durchzuführen

Revendications

1. Procédé de détermination d'au moins un paramètre d'intérêt d'un matériau, le procédé comprenant :

diriger, à l'aide d'un applicateur radiofréquence (RF), une ou plusieurs impulsions d'énergie RF dans une région d'intérêt, la région d'intérêt comprenant un matériau ayant un paramètre d'intérêt et au moins une référence, le matériau et la référence étant séparés par au moins une limite ;
détecter, à l'aide d'un récepteur acoustique, au moins un signal acoustique multipolaire généré dans la région d'intérêt en réponse aux impulsions d'énergie RF ; traiter le ou les signaux acoustiques multipolaires pour déterminer une intensité de champ électrique au niveau de la limite ;
calculer un rapport d'ondes stationnaires de tension (VSWR) de la ou des impulsions d'énergie RF ;
surveiller une puissance directe et une puissance réfléchie de la ou des impulsions d'énergie RF pour calculer le VSWR, et
déterminer le ou les paramètres d'intérêt du matériau sur la base au moins de l'intensité du champ électrique déterminée et du VSWR.

2. La méthode de la revendication 1, dans lequel au moins un paramètre d'intérêt étant l'un parmi un paramètre Gruneisen du matériau et une conductivité du matériau.

3. La méthode de la revendication 2, dans lequel au moins un paramètre d'intérêt sont un produit du paramètre Gruneisen du matériau et de la conductivité du matériau.

4. La méthode de la revendication 2, dans lequel au moins un paramètre d'intérêt étant une capacité thermique spécifique du matériau.

5. La méthode de la revendication 1, dans lequel une identité du matériau est connue.

6. La méthode de la revendication 5, dans lequel la détermination comprenant l'estimation du ou des paramètres d'intérêt.

7. La méthode de la revendication 1, dans lequel l'identité du matériau est inconnue.

8. La méthode de la revendication 7, dans lequel la détermination comprenant la recherche du ou des paramètres d'intérêt dans une table de recherche.

9. La méthode de la revendication 1, dans lequel l'intensité du champ électrique étant déterminée sur la base d'une puissance d'entrée de l'applicateur RF et d'un coefficient d'atténuation de la référence.

10. La méthode de la revendication 1,dans lequel l'intensité du champ électrique étant déterminée sur la base d'une

épaisseur estimée de la référence et d'un coefficient d'atténuation de la référence.

11. La méthode de la revendication 1, dans lequel chaque signal acoustique multipolaire correspond à un emplacement limite distinct.

12. La méthode de la revendication 1, la détection dudit signal acoustique multipolaire étant réalisée à l'aide d'un système d'imagerie thermoacoustique.

13. Système pour déterminer au moins un paramètre d'intérêt d'un matériau, le système comprenant une référence ; un système d'imagerie thermoacoustique (26) comprenant un applicateur radiofréquence (RF) (36) configuré pour émettre des impulsions d'énergie RF dans la zone d'intérêt comprenant un matériau ayant au moins un paramètre d'intérêt et une référence, le matériau et la référence étant séparés par au moins une frontière, un récepteur acoustique (28) configuré pour recevoir au moins un signal acoustique multipolaire généré dans la zone d'intérêt en réponse aux impulsions d'énergie RF, ledit au moins un signal acoustique multipolaire étant une onde de pression acoustique ;

un premier moniteur de puissance pour mesurer la puissance directe des impulsions d'énergie RF ;
un deuxième moniteur de puissance pour mesurer la puissance réfléchie des impulsions d'énergie RF ; et
un ou plusieurs processeurs (22) configurés à cet effet :

traiter des signaux acoustiques multipolaires reçus par le récepteur acoustique afin de déterminer une intensité de champ électrique à la frontière ;
calculer un rapport tension/ondes stationnaires (VSWR) des une ou plusieurs impulsions d'énergie RF ;
surveiller une puissance directe et une puissance réfléchie de l'impulsion ou des impulsions d'énergie RF afin de calculer le VSWR ; et
déterminer le au moins un paramètre d'intérêt du matériau sur la base au moins de l'intensité de champ électrique déterminée et du VSWR.

14. Le système de la revendication 13, dans lequel au moins un paramètre d'intérêt étant l'un parmi un paramètre Gruneisen du matériau et une conductivité du matériau.
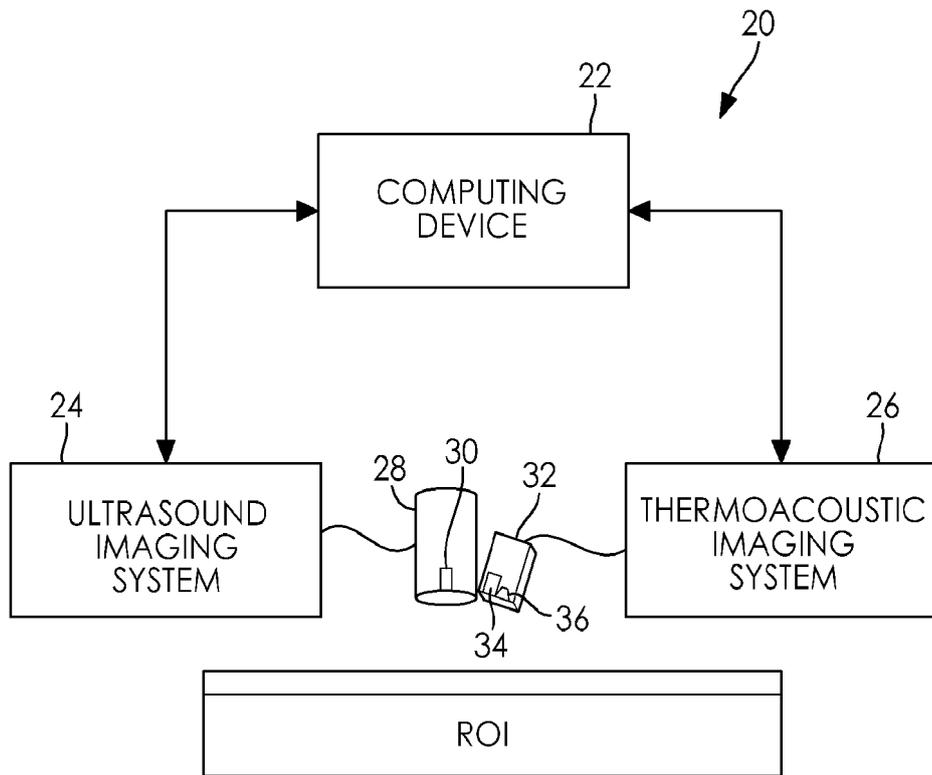
15. Le système de la revendication 14, dans lequel au moins un paramètre d'intérêt étant un produit du paramètre Gruneisen du matériau et de la conductivité du matériau.

16. Le système de la revendication 14, dans lequel au moins un paramètre d'intérêt étant une capacité thermique spécifique du matériau.
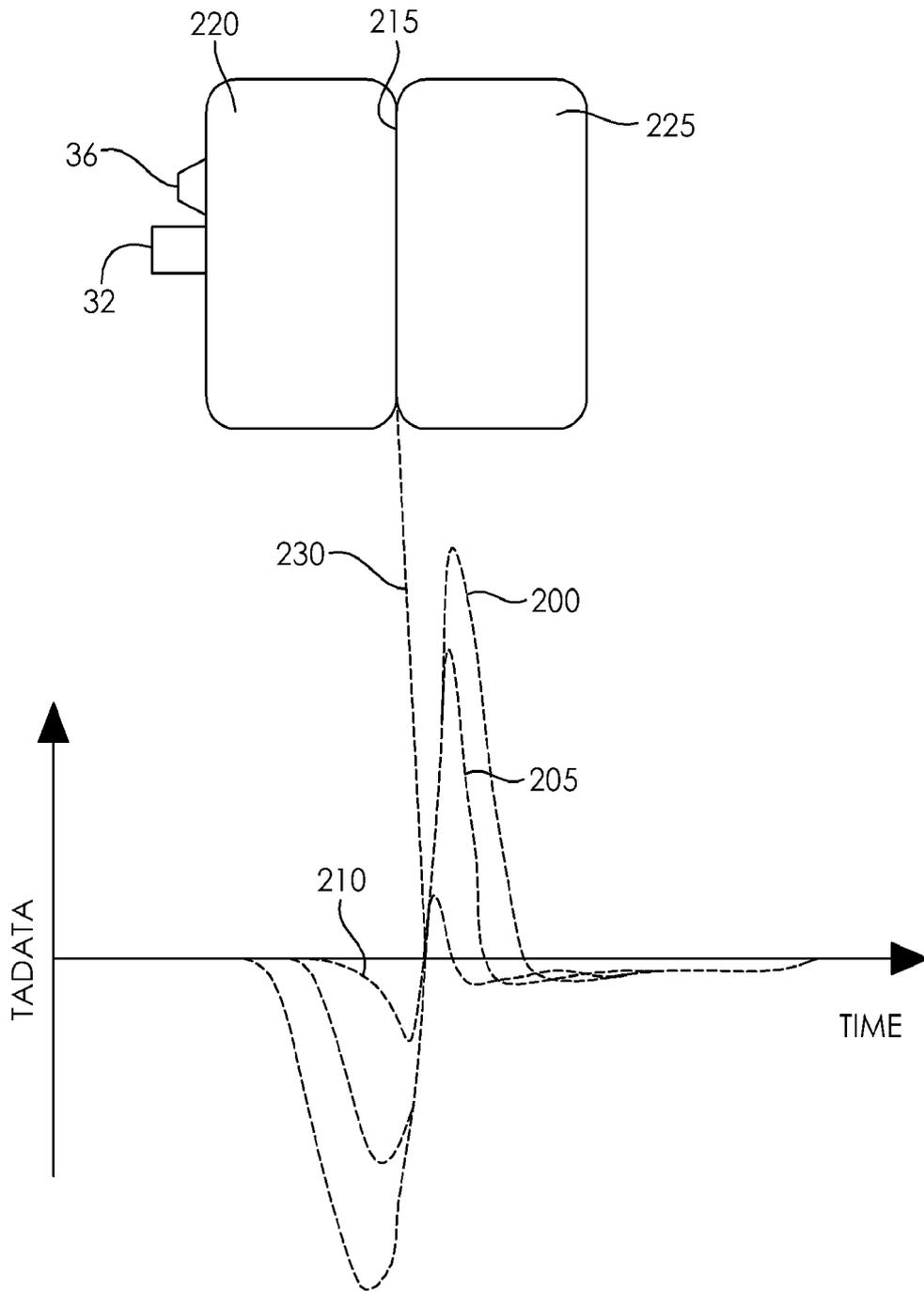
17. Le système de la revendication 13, comprenant en outre au moins un moniteur de puissance configuré pour surveiller une puissance directe et réfléchie des impulsions d'énergie RF, et le ou les processeurs sont configurés pour calculer le VSWR à l'aide de la puissance directe et réfléchie des impulsions d'énergie RF.

18. Le système de la revendication 13, dans lequel l'intensité du champ électrique étant déterminée sur la base d'une puissance d'entrée de l'applicateur RF et d'un coefficient d'atténuation de la référence.
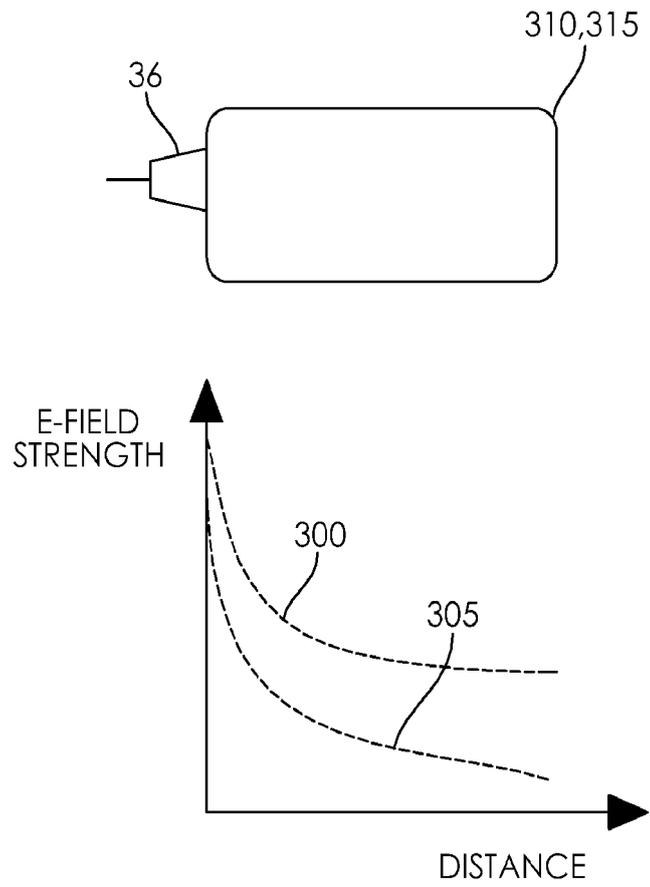
19. Support lisible par ordinateur non transitoire sur lequel est stocké un code de programme informatique exécutable par un ou plusieurs processeurs et faire en sorte que le système de l'une des revendications 13 à 18 exécute les étapes de l'une des revendications 1 à 12
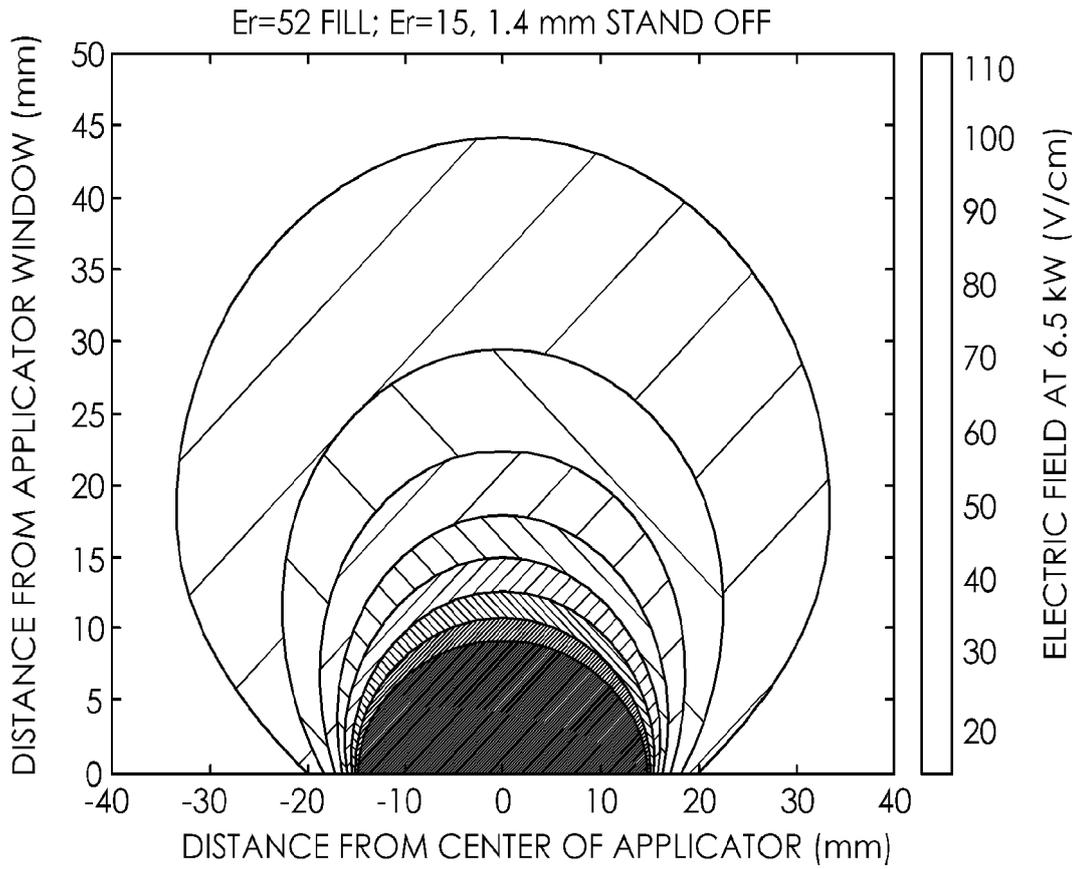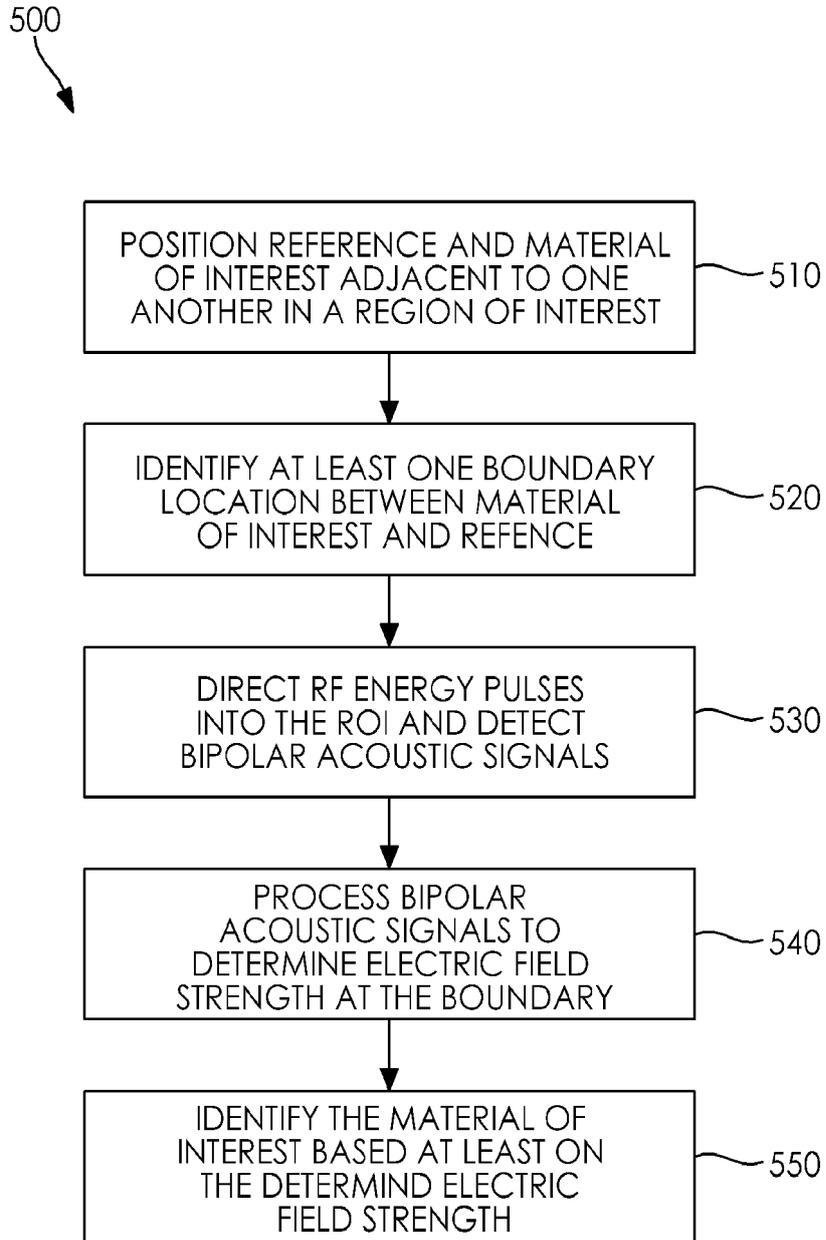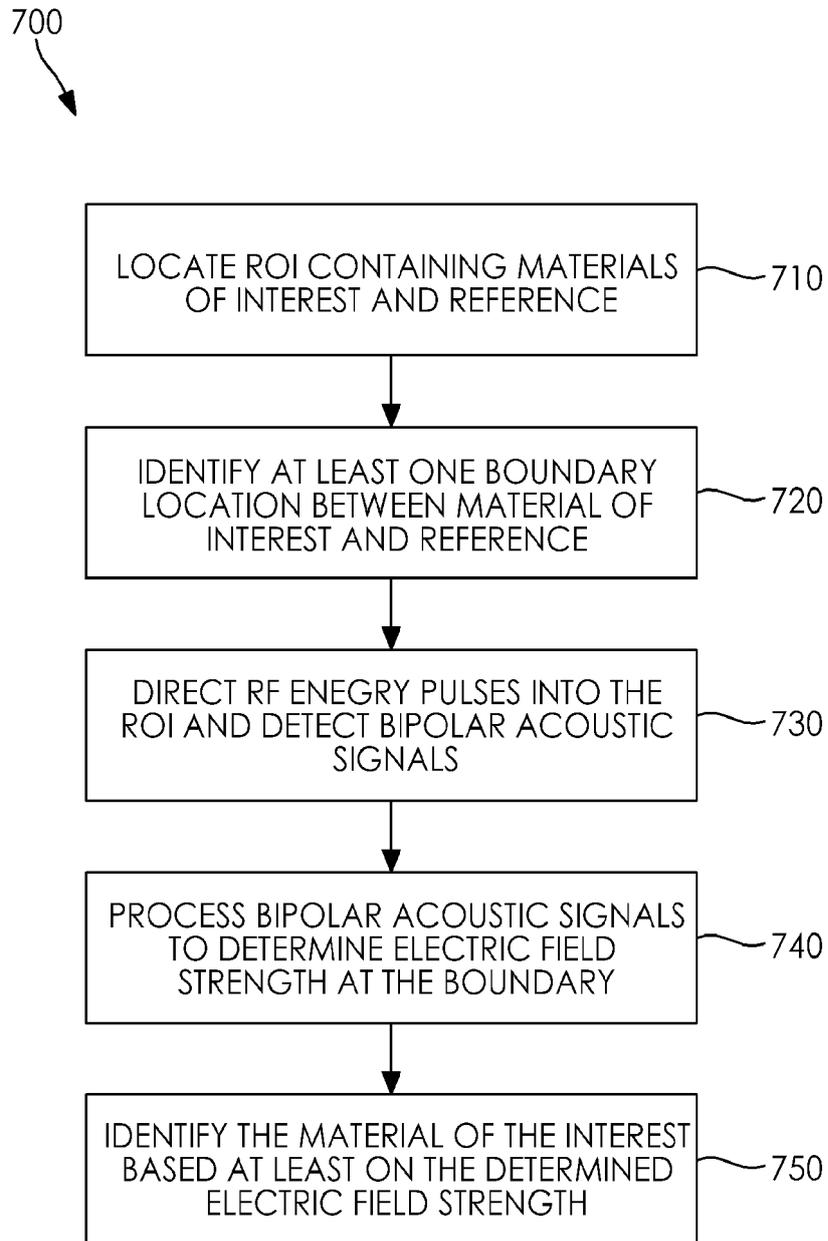
FIG. 1

FIG. 2

FIG. 3

FIG. 4

500

POSITION REFERENCE AND MATERIAL
OF INTEREST ADJACENT TO ONE
ANOTHER IN A REGION OF INTEREST — 510

IDENTIFY AT LEAST ONE BOUNDARY
LOCATION BETWEEN MATERIAL
OF INTEREST AND REFENCE — 520

DIRECT RF ENERGY PULSES
INTO THE ROI AND DETECT
BIPOLAR ACOUSTIC SIGNALS — 530

PROCESS BIPOLAR
ACOUSTIC SIGNALS TO
DETERMINE ELECTRIC FIELD
STRENGTH AT THE BOUNDARY — 540

IDENTIFY THE MATERIAL OF
INTEREST BASED AT LEAST ON
THE DETERMIND ELECTRIC
FIELD STRENGTH — 550

FIG. 5

700

LOCATE ROI CONTAINING MATERIALS
OF INTEREST AND REFERENCE — 710

IDENTIFY AT LEAST ONE BOUNDARY
LOCATION BETWEEN MATERIAL OF
INTEREST AND REFERENCE — 720

DIRECT RF ENEGRY PULSES INTO THE
ROI AND DETECT BIPOLAR ACOUSTIC
SIGNALS — 730

PROCESS BIPOLAR ACOUSTIC SIGNALS
TO DETERMINE ELECTRIC FIELD
STRENGTH AT THE BOUNDARY — 740

IDENTIFY THE MATERIAL OF THE INTEREST
BASED AT LEAST ON THE DETERMINED
ELECTRIC FIELD STRENGTH — 750

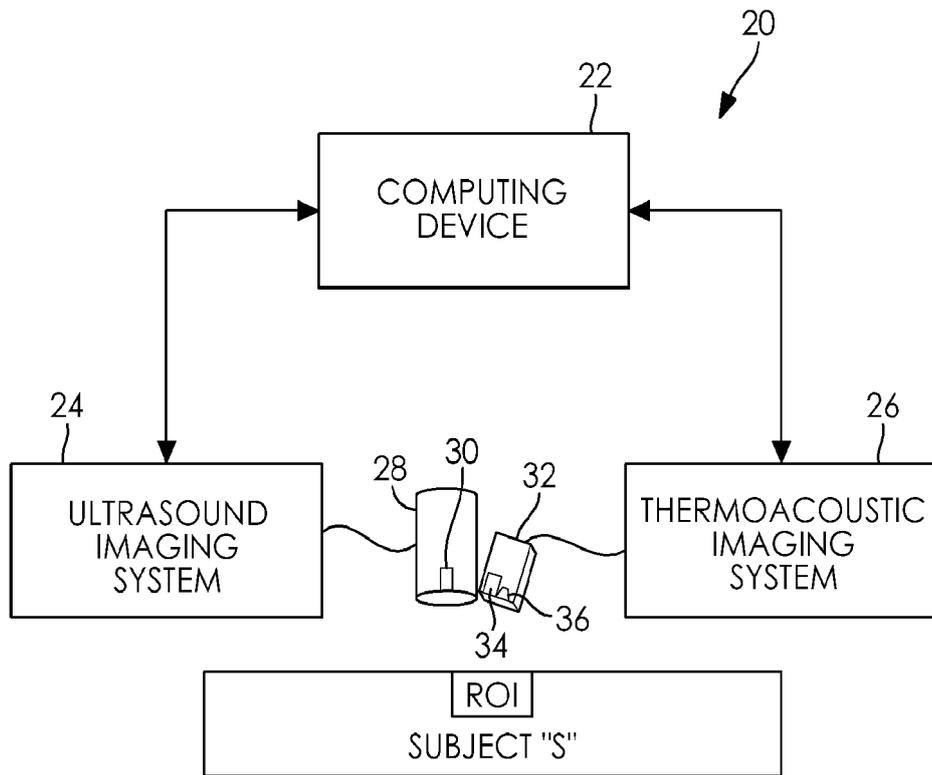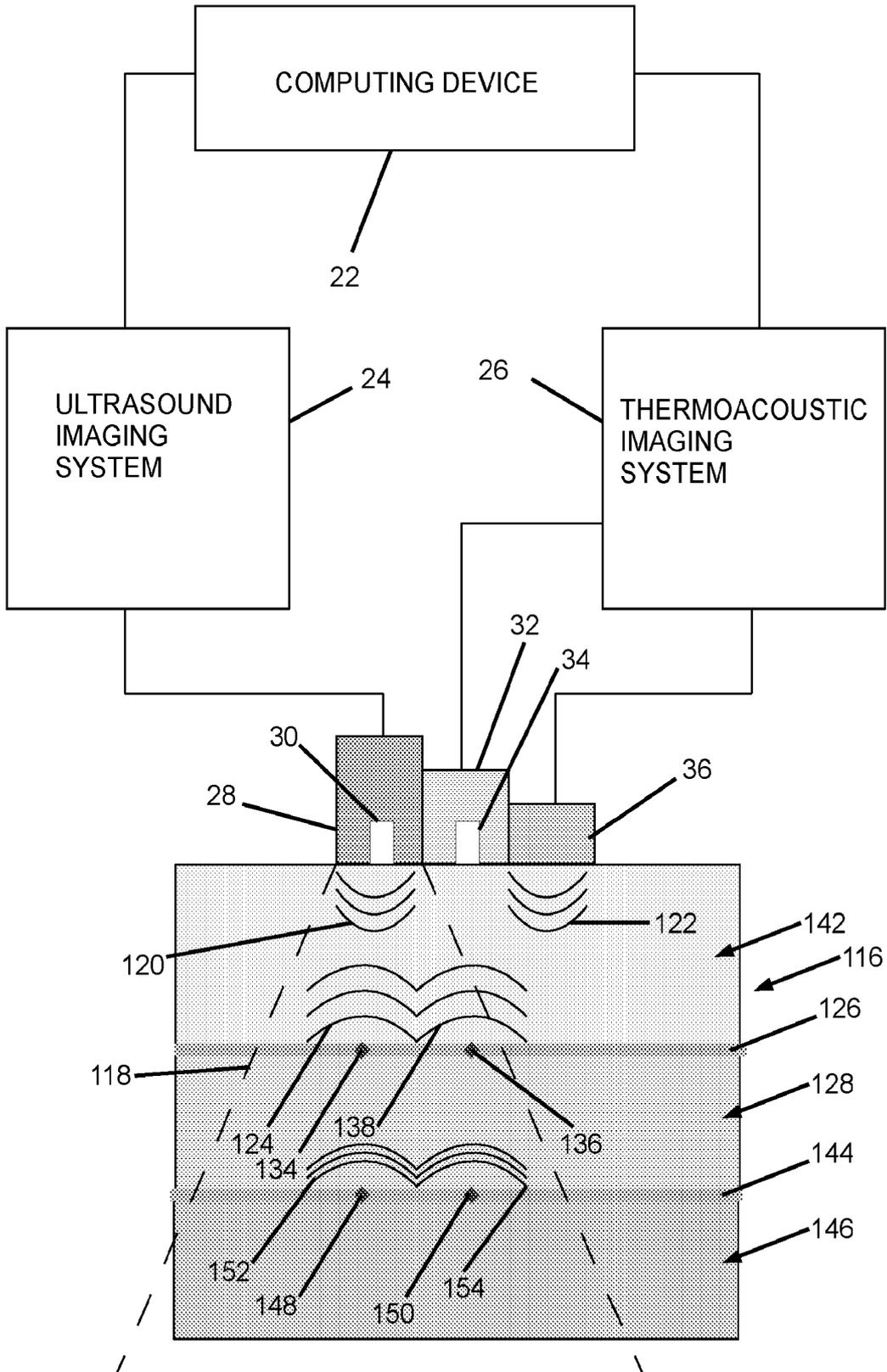## FIG. 6

FIG. 7

FIG. 8

REFERENCES CITED IN THE DESCRIPTION

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