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Roldán-Alzate et al.

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(54) **SYSTEMS AND METHODS FOR MAGNETIC RESONANCE PHANTOMS**

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A61B 5/00 (2006.01)
A61B 5/055 (2006.01)

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CPC ***G01R 33/58*** (2013.01); ***G01R 33/30*** (2013.01); *A61B 5/055* (2013.01); *A61B 5/4244* (2013.01)

(58) **Field of Classification Search**
USPC 324/18
See application file for complete search history.

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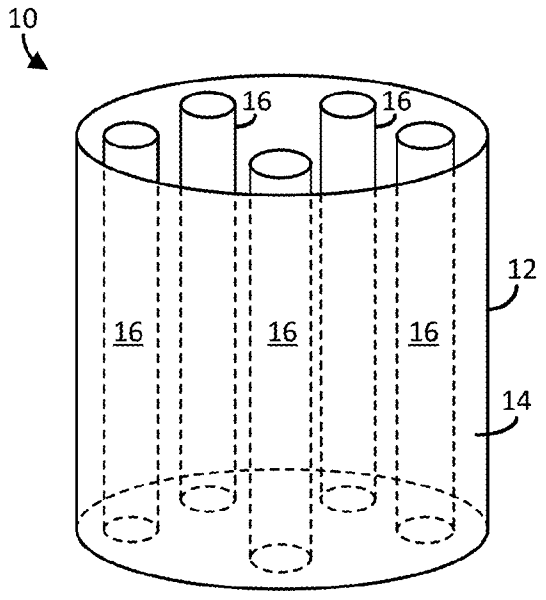
(57) **ABSTRACT**

In some embodiments, the present disclosure discloses a magnetic resonance (MR) phantom. The MR phantom includes a housing, a base medium disposed within the housing, and one or more compartment extending through the base medium, the one or more compartment comprising a crosslinked acrylamide-based polymer. The MR phantoms may be used as calibration phantoms for magnetic resonance elastography sequences and diffusion weighted images.

21 Claims, 4 Drawing Sheets



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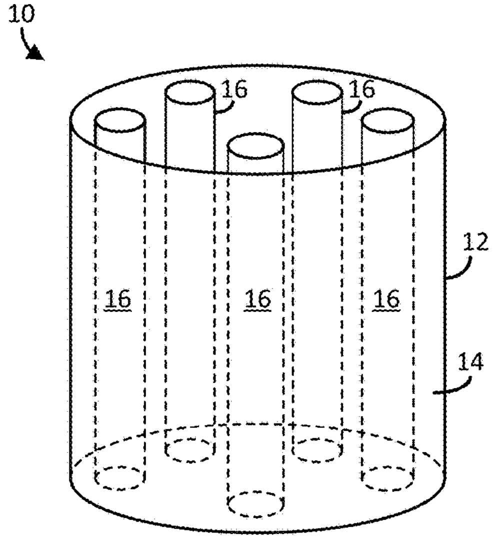


FIG. 1

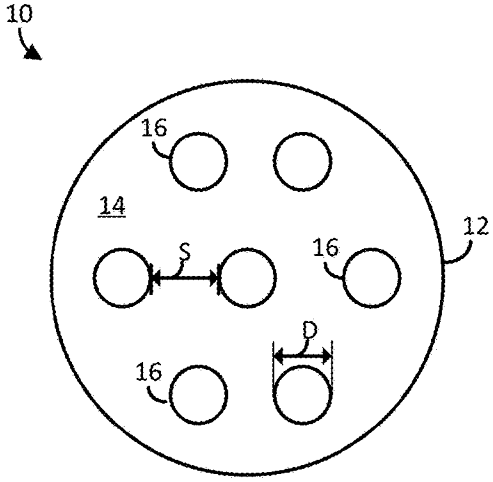


FIG. 2

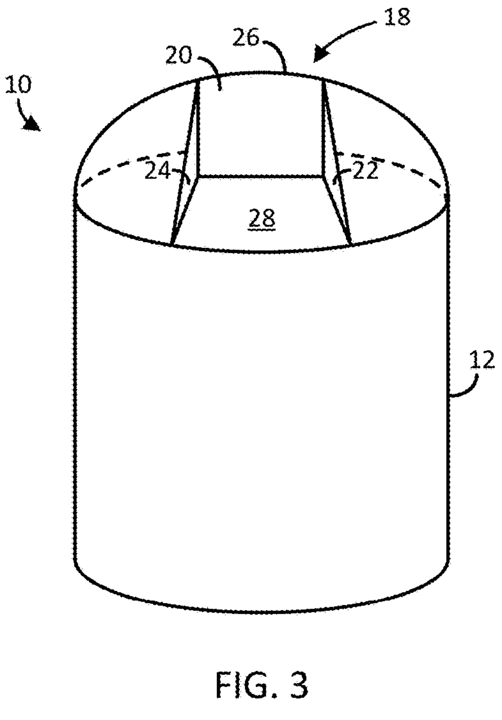
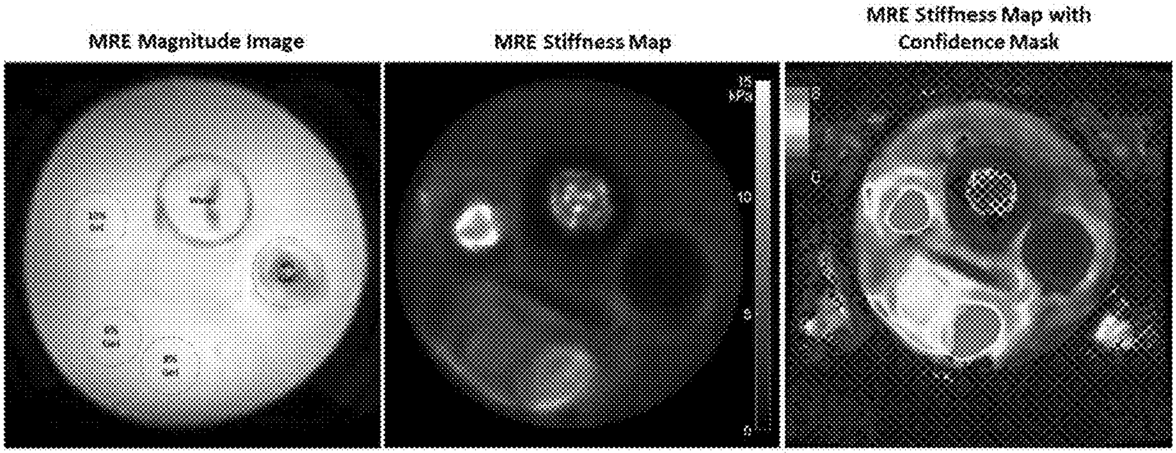


FIG. 3


MRE Magnitude Image

MRE Stiffness Map

MRE Stiffness Map with Confidence Mask

FIG. 4

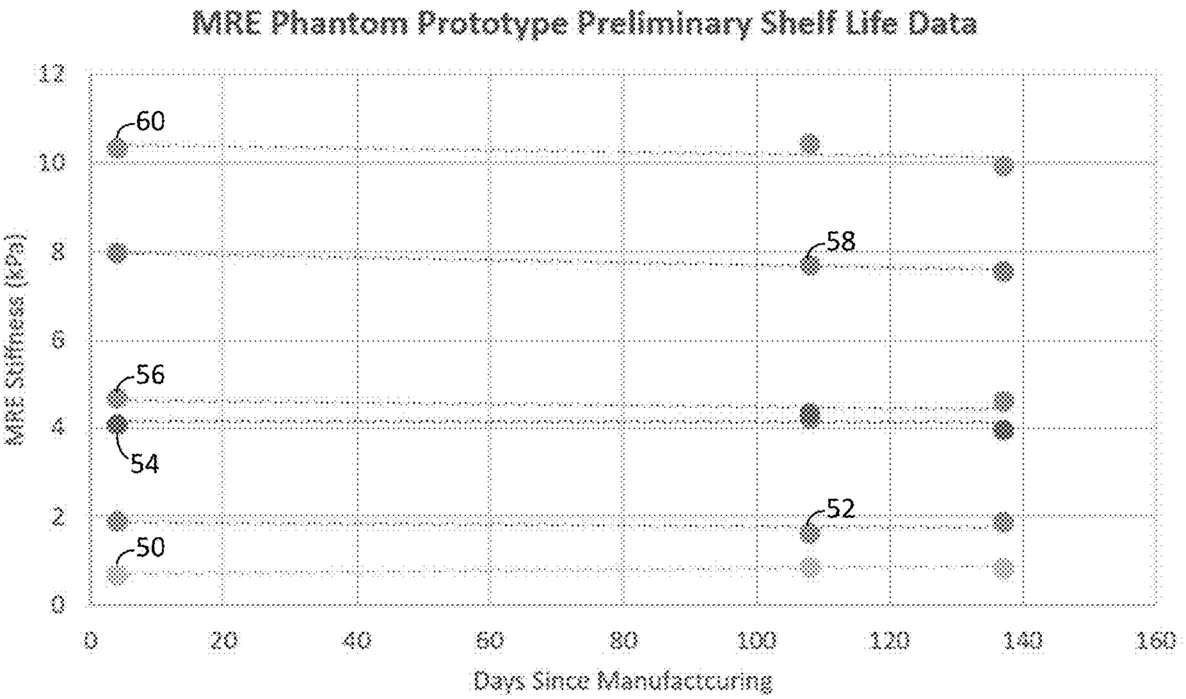


FIG. 5

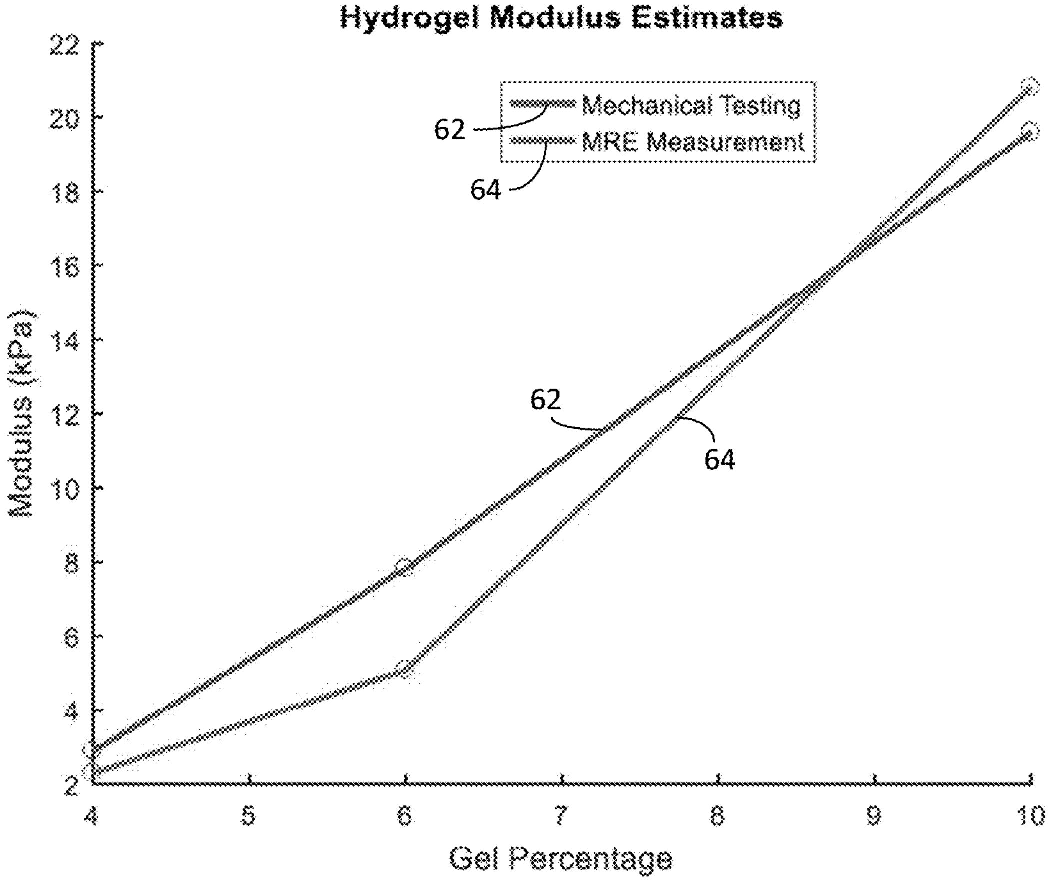

Hydrogel Modulus Estimates
Mechanical Testing
MRE Measurement
62
64
62
64
Modulus (kPa)
22
20
18
16
14
12
10
8
6
4
2
Gel Percentage
4
5
6
7
8
9
10

FIG. 6

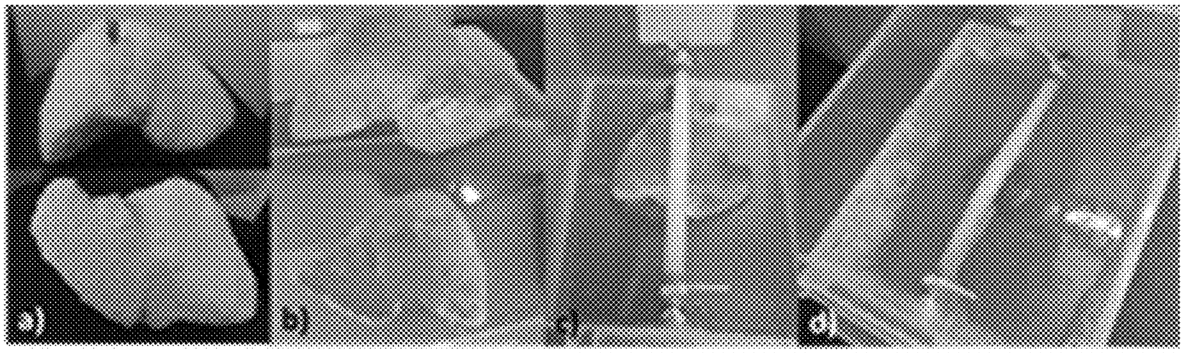


FIG. 7

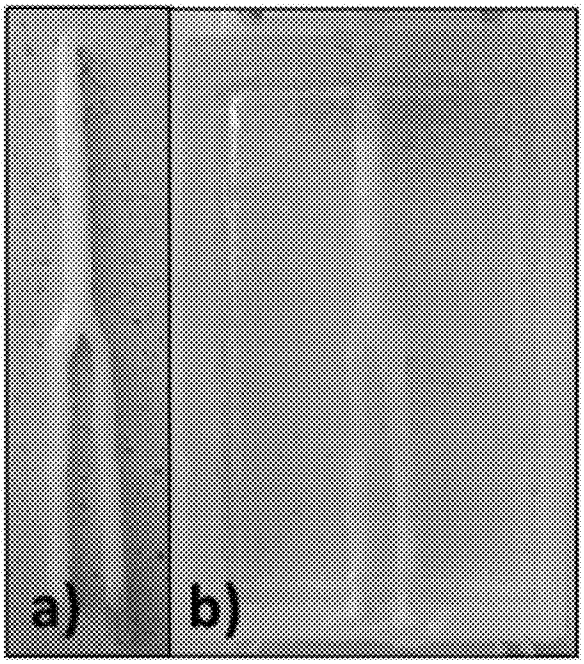


FIG. 8

SYSTEMS AND METHODS FOR MAGNETIC RESONANCE PHANTOMS

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

This invention was made with government support under DK117354 and EB025729 awarded by the National Institutes of Health. The government has certain rights in the invention.

BACKGROUND

Medical imaging is a fundamental resource in the modern practice of clinical medicine. The ability to acquire anatomical, physiological, and pathological information about the patient non-invasively makes medical imaging ubiquitous in many clinical applications. Furthermore, medical imaging can be used to direct and deliver therapeutic or surgical procedures.

In all of these settings, medical imaging provides powerful resources for the practice of clinical medicine by providing the ability to secure patient-specific information. However, medical imaging often struggles when looking to assess information across patients, or even longitudinally for a given patient. This occurs because medical imaging systems reflect a great deal of variability, such as between imaging modalities, system manufacturers, clinical implementations, or the like.

For example, magnetic resonance imaging (MM) is well established as the gold standard for acquiring clinical data in a wide-variety of clinical applications. However, images of the same patient, even using the same type of MRI study, across different MRI systems can vary greatly. As just one example, a diffusion weighted imaging (DWI) study of the same patient performed at two different times using two different MRI systems, even when the MM systems were manufactured by the same manufacturer, can yield two very-different images, even when the underlying anatomy and physiology is unchanged.

Furthermore, increasing the complexity of the study, such as to include additional hardware systems that are coordinated with the MM system, such as is the case in magnetic resonance elastography (MRE), can further increase the variability caused by differences in systems, manufacturers, or even the technicians or clinicians involved in the studies.

Thus, there continues to be a need for systems and methods to facilitate the consistency and quality of medical imaging data and studies.

SUMMARY OF THE INVENTION

The present disclosure provides systems and methods for improving the operation, quality, and/or consistency of performing a magnetic resonance (MR) study by providing phantom systems and methods of operation that can be used with a variety of MR application, such as magnetic resonance elastography sequences and diffusion weighted imaging. A phantom may a comprise housing, a base medium disposed within the housing, and one or more compartment extending through the base medium. The one or more compartment may include a crosslinked acrylamide-based polymer.

In some configurations, the present disclosure provides a magnetic resonance phantom comprising a sealed compartment and a hydrogel disposed in the sealed compartment. The hydrogel comprises a crosslinked acrylamide-based polymer and a solvent, the crosslinked acrylamide-based polymer comprising (i) at least 50 wt % of a polymerized acrylamide monomer, based on the total weight of the acrylamide-based polymer; and (ii) less than 10 wt % of a crosslinking agent, based on the total weight of the crosslinked acrylamide-based polymer.

These and other advantages and features of the invention will become more apparent from the following detailed description of the preferred embodiments of the invention when viewed in conjunction with the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

FIG. **1** is perspective view of a magnetic resonance (MR) phantom apparatus in accordance with some embodiments of the present disclosure.

FIG. **2** is top, cross-sectional view of a MR phantom apparatus in accordance with some embodiments of the present disclosure.

FIG. **3** is a perspective view of a MR phantom in accordance with some embodiments of the present disclosure.

FIG. **4** are magnetic resonance elastography images taken of an exemplary MR phantom apparatus in accordance with some embodiments of the present disclosure.

FIG. **5** is a graph of longitudinal stiffness measurements taken during magnetic resonance elastography excitations in accordance with some embodiments of the present disclosure.

FIG. **6** is a graph of magnetic resonance elastography parameters taken of an exemplary MR phantom apparatus in accordance with some embodiments of the present disclosure.

FIG. **7** is an example anthropomorphic hydrogel in the geometric shape of a liver in accordance of some embodiments of the present disclosure. The anthropomorphic motion phantom was created by a) designing a latex mold b) filling with hydrogel material and extracting a liver shaped volume c) fixing the hydrogel liver under a motion driver, and d) surrounding the liver with agar for improved imaging.

FIG. **8** is an example anthropomorphic hydrogel in a carotid bifurcation vessel geometry in accordance of some embodiments of the present disclosure. A) is the bifurcation core and b) is the finished hydrogel model with a vessel void.

DETAILED DESCRIPTION

As noted above, magnetic resonance imaging (MRI) is a highly-valuable resource in the practice of modern clinical medicine. MRI finds application is a very-wide variety of clinical settings. For example, chronic liver disease (CLD) is one of the leading causes of death in the United States and is a major public health burden. Early detection and disease tracking through liver biopsy can help prevent fibrosis progression and better inform treatment planning. However, biopsy procedures carry non-negligible risk, and are prone to high rates of sampling error and observer variability. MRI can be used as a tool to study CLD.

In particular, elastography, or elasticity imaging, has emerged as a viable alternative for analysis of liver fibrosis. Original elastography methods were performed with ultrasound imaging. However, ultrasound elastography has a number of limitations specific to the CLD population and tends to have high failure rates. Magnetic Resonance Elastography (MRE) is an MRI-based alternative that has demonstrated higher diagnostic accuracy than ultrasound elastography. MRE is currently known as one of the most accurate non-invasive methods for identifying, diagnosing, and tracking liver fibrosis, according to a number of professional organizations and associations and can be easily added to the end of a clinical MRI exam. However, like other quantitative biomarkers, a reference standard for liver stiffness measurement is needed for quality assurance (QA) in imaging studies and facilitate consistency, across studies, including across hardware platforms and the like.

As another example, diffusion weighted imaging (DWI) is an MRI method to evaluate the molecular function and micro-architecture of the human body. DWI signal contrast can be quantified by apparent diffusion coefficient maps and it acts as a tool for treatment response evaluation and assessment of disease progression. Ability to detect and quantify the anisotropy of diffusion leads to a new paradigm called diffusion tensor imaging (DTI). DTI is a tool for assessment of the organs with highly organized fiber structure. DWI forms an integral part of modern state-of-art magnetic resonance imaging and is indispensable in neuroimaging and oncology. DWI is a field that has been undergoing rapid technical evolution and its applications are increasing every day. Here too, improved standards are needed to achieve quality assurance (QA) in imaging studies and facilitate consistency, across studies, including across hardware platforms and the like.

The present disclosure provides a magnetic resonance (MR) phantom apparatus. As will be described, the MR phantom apparatus of the present disclosure provides substantial advantages over traditional phantoms. For example, traditional phantoms suffer from "drift" or variability over time as the materials of the phantom change, such as dehydrating or the like. Some phantoms lack dynamic range, form healthy to pathological ranges. Also, phantoms struggle to mimic both the anatomical and physiological conditions that are the focus of particular imaging studies. The MR phantom systems and methods provided herein overcome these shortcomings to provide substantial improvements for a variety of clinical applications, such as MRE and DWI.

Referring to FIGS. **1-2**, one example of a MR phantom apparatus **10** in accordance with the present disclosure is shown. The MR phantom apparatus **10** includes a housing **12** having a base medium **14** disposed within the housing **12**, and one or more compartment **16** extending through the base medium **14**.

In some configurations, the housing **12** includes walls that form a geometric shape and enclose an interior volume. Exemplary geometric shapes include, but are not limited to, a sphere, a cylinder, regular and irregular prisms, such as triangular prisms, cube prisms, rectangular prisms. In some configurations, the housing **12** has a cross-sectional shape that is an ellipse. Non-limiting example ellipse shapes include circle, oval, and ovoid. In some embodiments, the housing **12** is composed of a transparent plastic. Example transparent plastics include, but are not limited to, acrylic and polycarbonate.

In some configurations, the housing **12** includes one or more compartments **16** composed of a polymer matrix material. As used herein, the term "polymer" may refer to a compound prepared by polymerizing monomers, whether of the same or a different type, that in polymerized form provide the multiple and/or repeating "units" or "mer units" that make up a polymer. The generic term polymer thus embraces the term homopolymer, usually employed to refer to polymers prepared from only one type of monomer, and the term copolymer, usually employed to refer to polymers prepared from at least two types of monomers. It also embraces all forms of copolymers, e.g., random, block, etc. It is noted that although a polymer is often referred to as being "made of" one or more specified monomers, "based on" a specified monomer or monomer type, "containing" a specified monomer content, or the like, in this context the term "monomer" is understood to be referring to the polymerized remnant of the specified monomer and not to the unpolymerized species. In general, polymers herein are referred to has being based on "units" that are the polymerized form of a corresponding monomer.

In some configurations, the one or more compartments **16** may include a crosslinked acrylamide-based polymer. As used herein, the term "acrylamide-based polymer" may refer to a polymer that contains one or more polymerized acrylamide monomer and, optionally, may contain at least one comonomer. The terms "acrylamide-based polymer" and "polyacrylamide" may be used interchangeably.

As used herein, the phrase "crosslinked polymer" may refer to a polymer that contains a monomer (e.g., acrylamide) that has been copolymerized with one or more crosslinking agent comonomer (e.g., N—N'-methylene-bis-acrylamide or "bis"). Suitable crosslinking agents include bifunctional comonomer reagents that induce crosslinks, or covalent bonds, between linear polyacrylamide chains creating a network of covalently bonded polyacrylamide, rather than unconnected linear chains of polyacrylamide. As used herein, the terms "acrylamide/crosslinking agent" or "acrylamide/N—N'-methylene-bisacrylamide" may be indicative of a copolymer as described above prepared from polymerizing an acrylamide monomer with one or more crosslinking comonomer. Such a process may be induced using activating agents such as tetramethyl ethylenediamine (TEMED) and ammonium persulfate.

In some configurations, the polymerized acrylamide monomer constitutes greater than 50 wt % based on the total weight of the crosslinked acrylamide-based polymer. In some configurations, the polymerized acrylamide monomer constitutes from 50 wt % to 99 wt % based on the total weight of the crosslinked acrylamide-based polymer. In some configurations, the polymerized acrylamide monomer constitutes at least 50 wt %, or at least 55 wt %, or at least 60 wt %, or at least 65 wt %, or at least 70 wt %, or at least 75 wt %, or at least 80 wt %, or at least 85 wt %, or at least 90 wt %, to less than 91 wt %, or less than 92 wt %, or less than 93 wt %, or less than 94 wt %, or less than 95 wt %, or less than 96 wt %, or less than 97 wt %, or less than 98 wt %, or less than 99 wt %, based on the total weight of the crosslinked acrylamide-based polymer.

In some configurations, the crosslinking agent constitutes less than 10 wt % based on the total weight of the crosslinked acrylamide-based polymer. In some configurations, the crosslinking agent constitutes from 0.01 wt % to 10 wt %. In some configurations, the crosslinking agent constitutes at least 0.1 wt %, or at least 0.5 wt %, or at least 1 wt %, or at least 1.5 wt %, or at least 2 wt %, or at least 2.5 wt %, or at least 3 wt %, or at least 3.5 wt %, or at least 4 wt %, or at least 4.5 wt %, or at least 5 wt %, to less than 5.5 wt %, or less than 6 wt %, or less than 7 wt %, or less than 8 wt %, or less than 9 wt %, or less than 10 wt %, based on the total weight of the crosslinked acrylamide-based polymer.

In some configurations, acrylamide-based polymer is a hydrogel. As used herein, a "hydrogel" may refer to insoluble, crosslinked, three-dimensional networks of polymer chains having a solvent or dispersing medium that fills the voids between the polymer chains. In some configurations, the solvent or dispersing medium includes, but is not limited to, water, cell culture medium, buffers (e.g., phosphate buffered saline), a buffered solution (e.g. PBS), polyol (for example, glycerol, propylene glycol, liquid polyethylene glycol, and the like), Dulbecco's Modified Eagle Medium, fetal bovine serum, or suitable combinations and/or mixtures thereof.

In some configurations, the hydrogel in the one or more compartment **16** has a solvent or dispersing medium content from 50 wt % to 99.99 wt %, based on the total weight of the hydrogel. In some configurations, varying the solvent or dispersing medium content alters the mechanical stiffness or diffusion properties of the acrylamide-based polymer. In some configurations, the hydrogel has a solvent or dispersing medium content of at least 50 wt %, or at least 55 wt %, or at least 60 wt %, or at least 65 wt %, or at least 70 wt %, or at least 75 wt %, or at least 80 wt %, or at least 85 wt %, or at least 90 wt %, to less than 91 wt %, or less than 92 wt %, or less than 93 wt %, or less than 94 wt %, or less than 95 wt %, or less than 96 wt %, or less than 97 wt %, or less than 98 wt %, or less than 99 wt %, or less than 99.5 wt %, or less than 99.9 wt %, or less than 99.99 wt %, based on the total weight of the hydrogel.

In some configurations, the hydrogel in the one or more compartment **16** has an acrylamide-based polymer content from 0.01 wt % to 50 wt %, based on the total weight of the hydrogel. In some configurations, the hydrogel has an acrylamide-based polymer content of at least 0.01 wt %, or at least 0.05 wt %, or at least 0.1 wt %, or at least 0.5 wt %, or at least 1 wt %, or at least 2 wt %, or at least 3 wt %, or at least 4 wt %, or at least 5 wt %, or at least 6 wt %, or at least 7 wt %, or at least 8 wt %, or at least 9 wt %, or at least 10 wt %, to less than 11 wt %, or less than 12 wt %, or less than 13 wt %, or less than 14 wt %, or less than 15 wt %, or less than 20 wt %, or less than 30 wt %, or less than 40 wt %, or less than 50 wt %, based on the total weight of the hydrogel.

In some configurations, one or more of the compartments **16** may be a control compartment. The control compartment may include solvent or dispersing medium. In some configurations, the control compartment **16** is free of acrylamide-based polymers. In some configurations, the control compartment **16** consists only of solvent or dispersing medium.

Referring back to FIGS. **1**-**2**, the MR phantom apparatus **10** may include a plurality of compartments **16** having varying concentrations of acrylamide-based polymer and solvent or dispersing medium. Each compartment **16** may have a known mechanical stiffness or diffusion property (e.g., apparent diffusion coefficient). The MR phantom apparatus **10** can then be scanned by an MRI apparatus using imaging sequences, such as diffusion weighted imaging (DWI) or and magnetic resonance elastography images for various applications, such as calibrating the MM apparatus (e.g., using the phantom apparatus to calibrate "measured" parameters to "corrected" parameters), to perform clinical quality assurance, to perform site qualification for multi-center trials, or to aid in technical development and evaluation of new MRI procedures.

In some configurations, the MR phantom apparatus **10** contains at least two compartments **16**. In some configurations, the MR phantom apparatus **10** contains from 2 to 50 compartments **16**, or more. In some configurations, the MR phantom apparatus **10** contains at least 2 compartments **16**, or at least 3, or at least 4, or at least 5, or at least 6, or at least 7, or at least 8, or at least 9, to at least 10, or less than 15, or less than 20, or less than 25, or less than 30, or less than 35, or less than 40, or less than 45, or less than 50 compartments **16**.

In some configurations, each compartment **16** contains a different concentration of the acrylamide-based polymer. In some configurations, the compartments **16** form an array of concentrations that ranges from greater than, or equal to, 0 wt % to less than 50 wt % acrylamide-based polymer based on the total weight of components in each compartment in the array, or from greater than, or equal to, 0 wt % to less than, or equal to, 45 wt %, or from greater than, or equal to, 0 wt % to less than 40 wt %, or from greater than, or equal to, 0 wt % to less than 35 wt %, or from greater than, or equal to, 0 wt % to less than 30 wt %, or from greater than, or equal to, 0 wt % to less than 25 wt %, or from greater than, or equal to, 0 wt % to less than 20 wt %, or from greater than, or equal to, 0 wt % to less than 15 wt %, or from greater than, or equal to, 0 wt % to less than 10 wt %, or from greater than, or equal to, 0 wt %, to less than 5 wt %, based on the total weight of components in each compartment in the array.

In some configurations, the compartments **16** have a spacing S within the housing **12**. In some configurations, the compartments **16** may or may not be evenly spaced apart within the housing **12**. The spacing S may be defined as the minimum distance between the outer surfaces of two adjacent compartments **16**. In some configurations, the spacing is at least 1 mm. In some configurations, the spacing is from 1 to 500 mm, or more. In some configurations, the spacing is at least 1 mm, or at least 2 mm, or at least 3 mm, or at least 4 mm, or at least 5 mm, or at least 6 mm, or at least 7 mm, or at least 8 mm, or at least 9 mm, to at least 10 mm, or less than 15 mm, or less than 20 mm, or less than 30 mm, or less than 40 mm, or less than 50 mm, or less than 60 mm, or less than 80 mm, or less than 90 mm, or less than 100 mm, or less than 200 mm, or less than 300 mm, or less than 400 mm, or less than 500 mm.

In some configurations, the compartments **16** have a geometric shape. The geometric shape of the compartments **16** may match or substantially match the geometric shape of the housing **12**. In some configurations, compartments **16** have geometric shape that is, but are not limited to, a sphere, a cylinder, regular and irregular prisms, such as triangular prisms, cube prisms, rectangular prisms. In some configurations, the compartments **16** have a cross-sectional shape that is an ellipse. In some configurations, the ellipse may be a circle, oval, or ovoid. In some configurations, the compartments **16** have an anthropomorphic shape indicative of human anatomy, such as an organ. In some configurations, the compartment **16** has an anthropomorphic shape of an organ including, but not limited to, heart, lungs, liver, pancreas, esophagus, stomach, gallbladder, intestines, colon, rectum, anus, hypothalamus, pineal body, thyroid, parathyroids, adrenals, kidney, ureters, bladder, urethra, tonsils, adenoids, thymus, spleen, muscles, brain, spinal cord, ovaries, fallopian tubes, uterus, vulva, vagina, testes, vas deferens, prostate, penus, cartilage, ligaments, and tendons.

In some configurations, the compartments **16** have a physical dimension D (e.g., diameter, width, and/or length) of at least 5 mm. In some configurations, the compartments **16** have a physical dimension D from 5 mm to 500 mm, or more. In some configurations, the compartments **16** have a physical dimension D of at least 5 mm, or at least 10 mm, or at least 15 mm, or at least 20 mm, or at least 25 mm, or at least 30 mm, or at least 35 mm, or at least 40 mm, or at least 45 mm, or at least 50 mm, to less than 60 mm, or less than 70 mm, or less than 80 mm, or less than 90 mm, or less than 100 mm, or less than 200 mm, or less than 300 mm, or less than 400 mm, or less than 500 mm.

In some configurations, the one or more compartments **16** extends from 5% to 100% of the length, height, or diameter of the housing **12**. In some configurations, the one or more compartments **16** extends at least 5% of the length, height, or diameter of the housing **12**, or at least 10%, or at least 25%, or at least 50%, or at least 75%, to less than 80%, or less than 85%, or less than 90%, or less than 95%, or less than 99%, or to 100% of the length or height of the housing **12**.

In some configurations, the one or more compartments **16** constitute at least 5% percent of the internal volume (v/v) of the housing **12**. In some configurations, the one or more compartment **16** constitute from 10% to 95% of the internal volume of the housing **12**. In some configurations, the one or more compartment **16** constitutes at least 10% (v/v), or at least 20%, or at least 30%, or at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90%, or at least 95% (v/v) of the internal volume of the housing **12**.

In some configurations, the one or more compartments **16** may be composed of a hydrogel that is encased in a material, such as a polymeric film or glass. In some configurations, the compartments **16** may form a sealed compartment. The sealed compartment may have a hermetic seal (i.e., is airtight) and/or a watertight seal. In some configurations, the glass may completely surround the hydrogel disposed in the one or more compartments **16**. In some configurations, the glass may have a re-sealable opening (e.g., a vial). Nonlimiting examples of suitable polymeric film materials include olefin-based polymers (including any ethylene/C3-C10 α-olefin copolymers linear or branched), propylene-based polymer (including plastomer and elastomer, random propylene copolymer, propylene homopolymer, and propylene impact copolymer), ethylene-based polymer (including plastomer and elastomer, high density polyethylene ("HDPE"), low density polyethylene ("LDPE"), linear low density polyethylene ("LLDPE"), medium density polyethylene ("MDPE"), ethylene-acrylic acid or ethylene-methacrylic acid and their ionomers with zinc, sodium, lithium, potassium, magnesium salts, ethylene vinyl acetate copolymers) and blends thereof.

In some configurations, the one or more compartment **16** may include a hydrogel having a material modulus from 1 kPa to 100 kPa. In some configurations, the one or more compartment **16** includes a hydrogel having a material modulus of at least 1 kPa, or at least 2 kPa, or at least 3 kPa, or at least 4 kPa, or at least 5 kPa, or at least 6 kPa, or at least 7 kPa, or at least 8 kPa, or at least 9 Kpa, or at least 10 kPa, or at least 15 kPa, to less than 20 kPa, or less than 25 kPa, or less than 30 kPa, or less than 35 kPa, or less than 40 kPa, or less than 45 kPa, or less than 50 kPa, or less than 75 kPa, or less than 100 kPa.

In some configurations, the one or more compartment **16** includes a hydrogel having an apparent diffusion coefficient (ADC) of less than 2.5×10^{-3} mm^2/s, or in some configurations, from 0.1×10^{-3} mm^2/s to 2.5×10^{-3} mm^2/s. In some configurations, the one or more compartment **16** includes a hydrogel having an ADC of at least 0.1×10^{-3} mm^2/s, or at least 0.2×10^{-3} mm^2/s, or at least 0.3×10^{-3} mm^2/s, or at least 0.4×10^{-3} mm^2/s, or at least 0.5×10^{-3} mm^2/s, or at least 0.6×10^{-3} mm^2/s, or at least 0.7×10^{-3} mm^2/s, or at least 0.8×10^{-3} mm^2/s, or at least 0.9×10^{-3} mm^2/s, or at least 1.0×10^{-3} mm^2/s, or at least 1.1×10^{-3} mm^2/s, or at least 1.2×10^{-3} mm^2/s, or at least 1.3×10^{-3} mm^2/s, or at least 1.4×10^{-3} mm^2/s, or at least 1.5×10^{-3} mm^2/s, or less than 1.6×10^{-3} mm^2/s, or less than 1.7×10^{-3} mm^2/s, or less than 1.8×10^{-3} mm^2/s, or less than 1.9×10^{-3} mm^2/s, or less than 2.0×10^{-3} mm^2/s, or less than 2.1×10^{-3} mm^2/s, or less than 2.2×10^{-3} mm^2/s, or less than 2.3×10^{-3} mm^2/s, or less than 2.4×10^{-3} mm^2/s, or less than 2.5×10^{-3} mm^2/s.

In some configurations, the MR phantom apparatus **10** includes a base medium **14**. The base medium **14** may partially or completely surround the one or more compartments **16** within the internal volume of the housing **12**. In some configurations, the base medium **14** is in direct contact with the one or more compartments **16** (e.g., the base medium may directly contact the hydrogel or acrylamide-based polymer in the one or more compartments **16**). In some configurations, the base medium **14** contacts the side surfaces of the one or more compartments **16**, but does not contact the top and/or bottom surfaces of the one or more compartments **16**. In some configurations, the base medium **14** includes a plurality of channels or voids sized to receive the one or more compartments **16**.

In some configurations, the base medium **14** includes a hydrogel. In some configurations, the base medium **14** includes hydrogel composed of the acrylamide-based polymer and a solvent and/or dispersing medium described above.

In some configurations, the hydrogel in the base medium **14** has a solvent or dispersing medium content from 50 wt % to 99.99 wt %, based on the total weight of the hydrogel. In some configurations, the hydrogel in the base medium **14** has a solvent or dispersing medium content of at least 50 wt %, or at least 55 wt %, or at least 60 wt %, or at least 65 wt %, or at least 70 wt %, or at least 75 wt %, or at least 80 wt %, or at least 85 wt %, or at least 90 wt %, to less than 91 wt %, or less than 92 wt %, or less than 93 wt %, or less than 94 wt %, or less than 95 wt %, or less than 96 wt %, or less than 97 wt %, or less than 98 wt %, or less than 99 wt %, or less than 99.5 wt %, or less than 99.9 wt %, or less than 99.99 wt %, based on the total weight of the hydrogel in the base medium **14**.

In some configurations, the hydrogel in base medium **14** has an acrylamide-based polymer content from 0.01 wt % to 50 wt %, based on the total weight of the hydrogel. In some configurations, the hydrogel has an acrylamide-based polymer content of at least 0.01 wt %, or at least 0.05 wt %, or at least 0.1 wt %, or at least 0.5 wt %, or at least 1 wt %, or at least 2 wt %, or at least 3 wt %, or at least 4 wt %, or at least 5 wt %, or at least 6 wt %, or at least 7 wt %, or at least 8 wt %, or at least 9 wt %, or at least 10 wt %, to less than 11 wt %, or less than 12 wt %, or less than 13 wt %, or less than 14 wt %, or less than 15 wt %, or less than 20 wt %, or less than 30 wt %, or less than 40 wt %, or less than 50 wt %, based on the total weight of the hydrogel in the base medium **14**.

In some configurations, the base medium **14** comprises or consists of a solvent or dispersing medium described above. In some configurations, the base medium **14** comprises or consists of a gas, such as air.

In some configurations, the base medium **14** constitutes at least 5% percent of the internal volume (v/v) of the housing **12**. In some configurations, the one or more compartment **16** constitute from 10% to 95% of the internal volume of the housing **12**. In some configurations, the one or more compartment **16** constitutes at least 10% (v/v), or at least 20%, or at least 30%, or at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90%, or at least 95% (v/v) of the internal volume of the housing **12**.

In some configurations, the one or more compartments **16** and/or the base medium **14** comprise a contrast agent. In some configurations, the contrast agent may be present in an amount of less than 10% based on the total weight of components in the one or more compartments **16** and/or the base medium **14**. Exemplary contrast agents include compounds and/or chemical moieties that enhance or alter imaging parameters (e.g., T_1 and/or T_2) during MM imaging. Exemplary contrast agents include salts, such as sodium chloride, nickel chloride, magnesium chloride, copper sulfate, and combinations thereof.

Referring now to FIG. **3**, a housing **12** is illustrated for the MR phantom apparatus **10** according to some configurations of the present disclosure. The housing **12** includes a recessed region **18**. The recessed region **18** may be sized to receive a passive driver for MRE imaging. In MRE imaging, active drivers are responsible for generating mechanical waves, which are transmitted to the region of interest on the patient by a passive driver connected to the active drive through a tube (e.g., plastic tube). In some configurations, the recessed region **18** is arranged such that the passive driver can transmit mechanical waves to the one or more compartments **16**.

FIG. **3** illustrates an exemplary recessed region **18** according to some configurations of the present disclosure. The recessed region **18** may include a central wall **20** that connects two opposing side walls **22**, **24**. The walls **18**, **22**, and **24** extend from an outer surface **26** towards the internal volume of the housing **12** to a base wall **28** or "seat portion" for receiving the passive driver. In some configurations, the base wall **28** or seat portion is parallel to the top and/or bottom surface of the one or more compartments **16**.

Although not illustrated in FIG. **3**, the recessed region **18** may have different geometric shapes. For example, the recessed region may have a prism as a geometric shape. Suitable prisms may form at least 3 interior faces in the housing **12** (e.g., a recessed region **18** formed from 3 walls extending toward the interior volume of the housing **12**, forming a triangular prism cut away shape), or at least 4 interior faces (e.g., a cube-like or rectangular-like recessed region similar to that illustrated in FIG. **3**), or to at least 5 interior faces (e.g., a slotted shape having two opposing surfaces and a back wall), or more faces. Each geometric shape may have at least one face that is parallel to the top and/or bottom surfaces of the one or more compartments **16**. The recessed region **18** may be sized so that the passive driver may be moved above each of the one or more compartments **16**.

EXAMPLES

The following examples are presented by way of illustration and are not meant to be limiting in any way.

MRE Phantom:

An MRE phantom with 5 compartments of varied mechanical stiffness was fabricated with polyacrylamide hydrogel. The hydrogel material base solution was created by dissolving two polymer components-acrylamide and bis-acrylamide (Fisher Scientific, Hampton, N.H., USA)- into de-ionized water. The stiffness of the hydrogel samples was varied by changing the percentage of polymer components dissolved in the water base. Gel percentages of each sample included in the phantom were 4%, 6%, 8%, and 10%. Cross-linking of the gel was initiated by the addition of Tetramethylethylenediamine (TEMED) and ammonium persulfate (Fisher Scientific, Hampton, N.H., USA).

Four hydrogel compartments were created by filling custom 3D-printed cylindrical molds with hydrogel of different stiffness properties. Portions of each sample material, along with additional samples of 12% and 16% gel, were poured into a separate container for later mechanical testing. The four cylinders were placed in a sealed, acrylic housing (7"×4") and surrounded by a fifth hydrogel of 6% gel composition. A cylindrical void of water was also included in the phantom.

MRE Images:

MRE stiffness images were obtained using a single-shot spin echo EPI pulse sequence on a 3T imaging system (SIGNA Premier, GE Healthcare, Waukesha, Wis.) using a 30 channel AIR™ coil and 60-channel posterior coil: scan time=5 min; TR=3000 ms; TE=71 ms; phase offsets=8; vibration frequency=60 Hz; vibration amplitude=50% max; slice thickness=3 mm; matrix=80×80. Mechanical vibrations were introduced using a soft, pillow-like driver through a pneumatic actuator (Resoundant, Rochester, Minn.). The phantom was placed on the pillow driver such that the cylinders were running vertically. MRE stiffness maps were obtained using a 3D direct inversion reconstruction. Regions of interest (ROI) measurements were manually drawn over all cylinders (including background material) in Matlab (Mathworks, Natick, Mass.).

Mechanical Analysis:

The hydrogel samples that were set aside during phantom fabrication were mechanically tested in unconfined compression and dynamic mechanical analysis. Cylindrical samples were made using biopsy punches on existing samples and by casting additional gels into 3D printed custom cylindrical molds. For unconfined compression testing, sample thickness was measured using calipers and samples were placed between two glass plates on a tabletop test machine equipped with a 1 kg load cell. A small tare load was applied, followed by a ramp to 10% strain at 0.10 s−1. Following testing, engineering strain and first Piola-Kirchhoff stress were calculated. A linear modulus was fit to the stress-strain data using custom MatLab code. Dynamic mechanical analysis was performed by applying an oscillatory strain to a sample and measuring the resulting sinusoidal stress with a Rheometrics Series RSA III system. From the stress magnitude, and corresponding phase delay from the input, the viscoelastic properties of the sample were recorded.

Results/Discussion:

A MRE phantom prototype was successfully created and withstood mechanical MRE vibration in the full range of MRE excitations. MRE stiffness maps are shown in FIG. **4**, and the longitudinal stiffness measurements are shown in FIG. **5**. FIG. **5** shows acrylamide/N—N'-methylene-bisacrylamide hydrogels at a 3% wt % (base medium hydrogel) 50, 4 wt % (compartment hydrogel) 52, 6 wt % (base medium hydrogel) 54, 6 wt % (compartment hydrogel) 56, 8 wt % (compartment hydrogel) 58, and 10 wt % (compartment hydrogel) 60. MRE scanning on separate hydrogel samples, including a 10% gel sample created with rapid polymerization, produced material modulus results comparable to results produce by mechanical analysis (FIG. **6**, mechanical testing 62, MRE measurement 64).

This example demonstrates a hydrogel-based MRE phantom with targeted material properties. The polyacrylamide gels used were highly adaptable within the desired tissue stiffness range. Furthermore, the high water content of these gels proved to be beneficial for general image quality. The acrylic phantom shell was also found to be beneficial, as it acted as a resonating excitation medium.

DWI Phantoms:

A diffusion phantom with 5 compartments of varied apparent diffusion coefficient (ADC) was fabricated with polyacrylamide hydrogel. The hydrogel material base solution was created by dissolving two polymer components-acrylamide and bis-acrylamide (Fisher Scientific, Hampton, N.H., USA)- into de-ionized water. The stiffness of the hydrogel samples was varied by changing the percentage of polymer components dissolved in the water base. Gel percentages of each sample included in the phantom were 8%, 15%, and 22%, and 30%. Cross-linking of the gel was initiated by the addition of Tetramethylethylenediamine (TEMED) and ammonium persulfate (Fisher Scientific, Hampton, N.H., USA).

Four hydrogel compartments were created by filling custom 3D-printed cylindrical molds with hydrogel of different stiffness properties. The four cylinders were placed in a sealed polypropylene housing and surrounded by a fifth hydrogel of 3% gel composition.

DWI Images:

Diffusion-weighted MRI images were obtained, and a wide range of diffusion values was quantified. A DWI pulse sequence applies diffusion sensitizing magnetic field gradients in selected directions during the MM measurement cycle to obtain MR images that have an image contrast related to the diffusion of water or other fluid molecules that occurred during the application of the diffusion gradients. Using these DWI images, an apparent diffusion coefficient (ADC) may be calculated for each voxel location in the reconstructed images.

Anthropomorphic Hydrogels

A hydrogel-based phantom was fabricated for testing motion-compensated diffusion MRI. This phantom consisted of an anthropomorphic hydrogel liver, an elastic tube motion driver, and agar, as shown in FIG. **7**. To create the anthropomorphic hydrogel liver, a liver model was first 3D-printed with polyvinyl-alcohol (PVA) filament on an Ultimaker (Utrecht, Netherlands) S5 machine. The PVA liver was then coated in liquid latex rubber. Once the rubber coating had dried, the inner PVA liver volume was dissolved with water, leaving a liver-shaped void in a rubber shell. An 8% acrylamide/N—N'-methylene-bisacrylamide hydrogel concentration was then poured into the rubber mold and allowed to polymerize. Once cured, the hydrogel liver was extracted from the rubber, placed in a water-tight container, and surrounded with agar gel. Compliant tubing was then run over the top of the liver model and fixed within the water-tight container. The ends of the tubing were then integrated into a flow loop with a pulsatile positive displacement pump (BDC PD-1100, BDC Laboratories, Wheat Ridge, Colo.). Water was pumped through the system, causing deformation of the compliant tube and adjacent hydrogel liver model at a frequency of one hertz. This setup was intended to mimic the cyclic motion induced by the cardiac pulse near the top of the liver in-vivo. Both standard and motion-compensated diffusion imaging were performed.

FIG. **8** illustrates a 3D printed carotid bifurcation vessel geometry fabricated for PC MRI and blood vessel motion analysis. The printed geometry was coated with silicone and set in a hydrogel of 12% gel concentration using the method described for the liver hydrogel of FIG. **7**. The vessel core was then dissolved from the hydrogel and fixed to the pulsatile pump system. 4D flow MRI and vessel displacement imaging were performed on the hydrogel model with a PC-VIPR.

The invention has been described according to one or more preferred embodiments, and it should be appreciated that many equivalents, alternatives, variations, and modifications, aside from those expressly stated, are possible and within the scope of the invention.

The preceding discussion is presented to enable a person skilled in the art to make and use embodiments of the invention. Various modifications to the illustrated embodiments will be readily apparent to those skilled in the art, and the generic principles herein can be applied to other embodiments and applications without departing from embodiments of the invention. Thus, embodiments of the invention are not intended to be limited to embodiments shown, but are to be accorded the widest scope consistent with the principles and features disclosed herein. The detailed description is to be read with reference to the figures, in which like elements in different figures have like reference numerals. The figures, which are not necessarily to scale, depict selected embodiments and are not intended to limit the scope of embodiments of the invention. Skilled artisans will recognize the examples provided herein have many useful alternatives and fall within the scope of embodiments of the invention.

It is to be understood that the disclosure is not limited in its application to the details of construction and the arrangement of components set forth in the description or illustrated in the drawings. The disclosure is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms "mounted," "connected," "supported," and "coupled" and variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings. Further, "connected" and "coupled" are not restricted to physical or mechanical connections or couplings.

We claim:

1. A magnetic resonance phantom comprising:

(i) a housing;

(ii) a base medium disposed within the housing; and

(iii) one or more compartment extending through the base medium, the one or more compartment comprising a crosslinked acrylamide-based polymer,

wherein the crosslinked acrylamide-based polymer is composed of an acrylamide/crosslinking agent copolymer.

2. The magnetic resonance phantom of claim **1**, wherein a polymerized acrylamide monomer constitutes at least 50 wt % based on the total weight of the acrylamide-based polymer.

3. The magnetic resonance phantom of claim **1**, wherein a polymerized crosslinking comonomer constitutes less than 10 wt % based on the total weight of the acrylamide-based polymer.

4. The magnetic resonance phantom of claim **1**, wherein the one or more compartment comprises a hydrogel, wherein the hydrogel comprises the crosslinked acrylamide-based polymer and a solvent or dispersing medium.

5. The magnetic resonance phantom of claim **4**, wherein the solvent or dispersing medium constitutes at least 50 wt % based on the total weight of the hydrogel.

6. The magnetic resonance phantom of claim **4**, wherein the acrylamide-based polymer constitutes less than 50 wt % based on the total weight of the hydrogel.

7. The magnetic resonance phantom of claim **4**, wherein the hydrogel has one or more of the following properties:

(a) an apparent diffusion coefficient from 0.1 to 2.5×10^{-3} mm^2/s; and

(b) a material modulus from 1 kPa to 100 kPa.

8. The magnetic resonance phantom of claim **1** comprising from 2 to 50 compartments.

9. The magnetic resonance phantom of claim **8**, wherein the compartments have a spacing from 1 mm to 100 mm.

10. The magnetic resonance phantom of claim **1**, wherein the one or more compartments have a diameter from 5 mm to 500 mm.

11. The magnetic resonance phantom of claim **1**, wherein the one or more compartments extend from 75% to 100% of the length or height of the housing.

12. The magnetic resonance phantom of claim **1** further comprising a plurality of compartments that form an array of acrylamide-based polymer concentrations that ranges from greater than, or equal to, 0 wt % to less than, or equal to, 50 wt % acrylamide-based polymer based on the total weight of components in each compartment in the array.

13. The magnetic resonance phantom of claim **1**, wherein the one or more compartments constitutes from 5% to 95% (v/v) of the internal volume of the housing.

14. The magnetic resonance phantom of claim **1**, wherein the base medium comprises a hydrogel.

15. The magnetic resonance phantom of claim **14**, wherein the one or more compartment forms a cylindrical shape having a top face, a bottom face, and body section that extends between the top face and the bottom face, the body section having an ellipse cross section, and

wherein the base medium completely surrounds the body section of the one or more compartment.

16. The magnetic resonance phantom of claim **1**, wherein the housing includes a hemispherical portion, wherein the hemispherical portion includes recessed region sized to receive a passive driver for magnetic resonance elastography imaging, and wherein the recessed region includes an interior face that is configured to allow the passive driver to transmit mechanical waves to the one or more compartments during magnetic resonance elastography imaging.

17. A magnetic resonance phantom comprising:

a sealed compartment;

a hydrogel disposed in the sealed compartment, the hydrogel comprising a crosslinked acrylamide-based polymer and a solvent, the crosslinked acrylamide-based polymer comprising:

(i) at least 50 wt % of a polymerized acrylamide monomer, based on the total weight of the acrylamide-based polymer; and

(ii) less than 10 wt % of a crosslinking agent, based on the total weight of the crosslinked acrylamide-based polymer.

18. The magnetic resonance phantom of claim **17**, wherein the sealed compartment is composed of a material selected from the group consisting of a polymeric film and glass.

19. The magnetic resonance phantom of claim **17**, wherein the hydrogel has an anthropomorphic shape.

20. A magnetic resonance phantom comprising:

(i) a housing;

(ii) a base medium disposed within the housing; and

(iii) one or more compartment extending through the base medium, the one or more compartment comprising a crosslinked acrylamide-based polymer,

wherein the one or more compartment comprises a hydrogel, wherein the hydrogel comprises the crosslinked acrylamide-based polymer and a solvent or dispersing medium.

21. A magnetic resonance phantom comprising:

(i) a housing;

(ii) a base medium disposed within the housing; and

(iii) a plurality of compartments extending through the base medium, the plurality of compartments comprising a crosslinked acrylamide-based polymer,

wherein the plurality of compartments form an array of acrylamide-based polymer concentrations that ranges from greater than, or equal to, 0 wt % to less than, or equal to, 50 wt % acrylamide-based polymer based on the total weight of components in each compartment in the array.

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