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REVIEW-SYMPOSIUM

Magnetic Resonance in Medicine

Summary and overview of the first ISMRM workshop on magnetic resonance elastography, August 25–26, 2022, Berlin, Germany

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Abstract

An ISMRM workshop on MR elastography was held at Charité–Universitätsmedizin Berlin on August 25–26, 2022. As an exclusively in-person event, 65 participants from 9 countries attended the workshop despite COVID-19–related restrictions. The topics of the workshop covered cellular and microtissue mechanical interactions, the development of MR elastography driver technology, approaches to inverse problems, clinical applications, and integration of MR elastography into multiparametric MRI protocols. The workshop was a great success by promoting direct knowledge exchange as well as for strategizing future directions for MR elastography. In this symposium review, we briefly summarized all oral presentations as well as the concluding panel discussion.

KEYWORDS

charité - univeristätsmedizin berlin, international workshop, ISMRM, MR elastography, MRE, study group

An ISMRM workshop on MR elastography (MRE) was held at Charité–Universitätsmedizin Berlin on August 25–26, 2022, as an exclusively in-person event, without online streaming of content. A total of 68 registered participants from countries attended the workshop. Other scientists informed the organizers that they were interested but unable to participate due to the relatively high registration fees and travel restrictions associated with COVID-19. A total of 10 student members from outside the organizers' institution received a grant that waived their conference fees. A total of 10 invited speakers gave keynote lectures covering a broad range of topics relevant for the development of MRE technology or the understanding of the signals acquired with MRE. Topics covering the development of driver technology, approaches to inverse problems, clinical applications, and how MRE might fit into multiparametric MRI protocols for characterizing renal or neuronal tissues were discussed and supplemented by keynote lectures on cellular and microtissue mechanical interactions. Overall, the workshop truly filled a gap, providing a long-awaited platform for the direct knowledge exchange within the community as well as for the planning of future strategies in terms of improved comparability, wider availability, and broader clinic accessibility. Photographs taken at the workshop are shown in Figure 1. Below is a brief summary of all oral presentations as well as a brief recap of the concluding panel discussion, based on notes of the organizers, who are the authors of this workshop review.

FIGURE 1 Photographs showing a moment during Steven Sourbron's talk (top left panel), the winners of the presenter awards (Siri Fløgstad Svensson, Yasmine Safraou, Anne-Sophie van Schelt, from left to right in the top right panel), and the participants of the panel discussion (bottom panel). Written consent for publication was obtained from the individuals in the top row, whereas all participants in the bottom row gave verbal agreement for publication

1 | KEYNOTE LECTURES (THURSDAY)

1.1 | MRE: State of the art and current challenges by Dieter Klatt, University of Illinois Chicago, IL, USA

This keynote lecture gave an overview of the history of MRE from many perspectives, starting with the evolution of different driver systems such as piezo-based drivers, pneumatic drivers, and eccentric mass drivers. This was followed by the fundamentals of measuring propagating waves and determining tissue mechanical properties by inversion methods. Another aspect covered challenges such as TE prolongation due to the use of motion-encoding gradients or long acquisition times and strategies to overcome them by fractional encoding or multicomponent acquisition, and faster acquisition using advanced 3D sequences. Finally, the lecture presented viscoelastic property reconstruction techniques by wave fitting, least-squares solutions, or inversion methods and discussed current challenges in treating compression waves, pressure, and anisotropy.

1.2 | Mechanical cell matrix interaction by Paul Janmey, University of Pennsylvania, PA, USA

Using dynamic mechanical analysis by shear rheometry—a ground-truth technique for the mechanical properties of soft tissue at low frequencies[1]—Paul Janmey addressed the fundamental question of which structural elements determine the macroscopic viscoelasticity of soft biological tissues, as seen by MRE. He outlined that, under compression, ex vivo tissues such as the brain and liver stiffen, whereas the cytoskeleton of isolated cells softens. Intriguingly and contrary to compression stiffening, soft tissues soften with increasing shear stress. Both compression stiffening and shear softening can be explained and modeled by considering the composite properties of cells, which are densely packed and surrounded by a relatively thin extracellular matrix (ECM). Whereas compression stiffening is determined by the compressibility of cells, shear softening is related to altered connectivity between cells and the ECM during loading. Recent investigations of fatty liver in obese mouse models have shown that compression stiffening increases sharply in later stages of fatty liver disease, whereas the shear-independent modulus is insensitive to liver steatosis.

1.3 | Cancer cell escape at the boundary between connective tissue and tumor by Josef Käs, University of Leipzig, Germany

Tissue mechanics in cancer is important to understand metastatic spread. In his keynote lecture, Josef Käs illustrated how the unjamming of cancer cells in breast tumors leads to the formation of microfluidic streams induced by changes in cell and nucleus shapes. Here, tension percolation transmits interactions between cell clusters with fluid behavior, making fluid bulk tumors stiff and rigid. In essence, cell density and shape determine unjamming of cancer cells, which might be a prerequisite for metastatic spread and hence might predict metastasis-free survival of breast cancer patients. Sensitized to unjamming, MRE could have an important role for the in vivo assessment of the metastatic potential of malignant tumors. In the second part, the talk detailed the role of adipose tissue for cancer progression, tumor inflammation, and as an energy source for tumors as well as the metabolic syndrome in favor of cancer.

1.4 | MRE in preclinical tumor models by Simon Robinson, The Institute of Cancer Research, London, UK

Tumor biomechanics is significantly altered, including fluid pressure, solid stress, and fibrous stiffening, which is the rationale for the development of MRE-based tumor markers. In a keynote lecture, Simon Robinson presented his group's research on rodent models of colorectal cancer and malignant brain tumors correlated with digital pathology to detect pixel-by-pixel microstructural changes including collagen deposition and vascular density. Tumors with dense stroma were shown to be much stiffer than tumors growing in neuronal tissue. The response of MRE to collagenase shows that the tumor softens in vivo, whereas hyaluronic acid digestion leads to increased stiffness and viscosity in breast tumor models, which could affect therapeutic outcome by stiffening the tumor. Moreover, stiffening has been shown to be an early tumor response to radiotherapy, consistent with ECM remodeling. Future research may focus on MRE in pancreatic ductal adenocarcinoma mouse models to investigate the relationship between ECM stiffness and immune responses in vivo and ultimately answer the question whether MRE can differentiate hot (inflamed) and cold (noninflamed) tumors.

2 | PROFFERED TALKS (THURSDAY)

2.1 | MRE for early assessment of response to neoadjuvant chemotherapy in women with breast cancer

2.1.1 | Presenter: Ralph Sinkus, Kings College, London, UK

An MRE study was presented that investigated metastatic propensity in 24 patients with breast cancer who were scanned 4 times after treatment and clinically classified according to microvascular invasion, lymph node invasion, or both. In this study, shear wave speed measured by MRE decreased significantly after treatment. Similarly, a preclinical model of head and neck tumors showed early treatment effects in the phase angle of the complex shear modulus. Whereas responders showed an increased phase angle, nonresponders showed a decreased phase angle, but with insignificant variations at later time points, probably due to masking effects occurring over time due to tissue adaptation to treatment.

2.2 | Increased stiffness on magnetic resonance elastography is an independent predictor of abdominal lymph node metastasis in solid tumors

2.2.1 | Presenter: Christian Neelsen, Charité Berlin and German Cancer Research Center (DKFZ), Berlin/Heidelberg, Germany

Lymph node (LN) staging is an important component of the clinical staging of solid tumors. However, it is recognized that standard criteria based on size are limited in the radiologic assessment of LN. Multifrequency MRE was performed in 21 tumor patients with LN metastases, and positron emission tomography–computed tomography was used as the reference standard. The results of this study show that MRE has a higher accuracy in detecting metastatic LNs than small axis diameter alone. Whereas stiffness was positively correlated to LN size, small lymph nodes (small axis diameter <10 mm) were only identified as malignant by higher stiffness.

2.3 | Radiosurgery inhibits tumor softening in a GL261 mouse model: Initial findings from in vivo murine tomoelastography

2.3.1 | Presenter: Anastasia Janas, Charité Berlin, Germany

Distinguishing between pseudo progression, radio necrosis, and post-therapeutic progression of glioblastoma continues to be a challenge for clinicians and radiologists. Therefore, stereotactic radiosurgery and multifrequency MRE were used in a glioblastoma mouse model. In this experiment, untreated glioblastoma was found to be softer than contralateral normal brain tissue. This softening appeared to be inhibited by a radiation dose of 20 Gy, whereas it was reversed by irradiation with 40 Gy at later follow-up time points.

2.4 | MR elastography of glioblastoma identifies regions with extracellular matrix reorganization

2.4.1 | Presenter: Siri Fløgstad Svensson, Oslo University Hospital, Norway

The study presented in this talk was undertaken to develop MRE biomarkers in glioblastoma and included 13 patients who underwent multifrequency wave excitation with a gravitational transducer. In each patient, 2–7 biopsies were taken and manually scored by the surgeon as stiffer as or softer than normal appearing brain tissue. In vivo MRE yielded higher stiffness values for most biopsies than ex vivo palpation. Gene signature distinguished stiffer from softer biopsies. Overall, patients with soft biopsies had better overall survival than those with stiff biopsies.

2.5 | Development of in vivo human brain multifrequency DTI-MRE: Preliminary results

2.5.1 | Presenter: Dieter Klatt, University of Illinois Chicago, IL, USA

Congruent acquisition of DTI and MRE data at the same time with 1 sequence can have several advantages for brain tissue characterization. DTI-MRE uses motion-encoding gradients for simultaneous acquisition of wave fields and water diffusion. MRE usually switches motion-encoding gradients between the 3 Cartesian axes. In DTI, the encoding is performed evenly spaced over a 3D sphere, and post-processing therefore requires the mapping of the phase projections onto MRE Cartesian axes. A study of 9 healthy subjects investigated with this new DTI-MRE technique was presented and compared with classical approaches of separate acquisitions.

2.6 | Neuroinflammation-associated stiffness changes of the cerebral cortex as novel imaging marker in multiple sclerosis

2.6.1 | Presenter: Rafaela Viera da Silva, Charité Berlin, Germany

MRE has great potential as a novel biomarker in multiple sclerosis. To investigate the involvement of cortical tissue in multiple sclerosis-related mechanical property changes of the brain, the mouse model of experimental autoimmune encephalitis was used to longitudinally monitor disease progression using multifrequency MRE. First, it was found that significant softening of cortical brain matter occurs in experimental autoimmune encephalitis, exceeding previously reported softening in other regions. Second, a correlational analysis of cortical brain matter softening was performed, which showed that MRE reflects disease severity, including reversed effects during remission and relapse. Finally, a mechanistic analysis of potentially relevant microstructural changes was performed based on histological quantification of perineuronal networks.

2.7 | Estimating brain tissue stiffness from cardiac-induced 7T MRI displacement measurements

2.7.1 | Presenter: Marius Burman Ingeberg, University Medical Center Utrecht, The Netherlands

Small vessel disease has high socioeconomic relevance but is a diagnostic challenge due to the resolution limits of standard MRI. Intrinsic brain pulsations were encoded at 7 Tesla in 8 healthy subjects using motion-sensitive high-resolution MRI. Brain displacement was encoded with displacement encoding with stimulated echoes and synchronized with the cardiac cycle. The wave equation accounting for local shear modulus and compressibility was solved. Unscaled shear modulus and compressibility values on the order of 200 and 125 Pa, respectively, were reconstructed, indicating relatively high compressibility of the brain at very low frequencies near 1 Hz.

2.8 | Direct estimation of transversely isotropic parameter variance from 3D displacement data to predict MR elastography reconstruction quality

Presenter: Elijah Van Houten, Université de Sherbrooke, Canada

This presentation reported the use of the nearly incompressible transverse isotropic (NITI) model to reconstruct shear modulus, shear anisotropy, or tensor anisotropy. Stress tensor variation was calculated to evaluate octahedral shear strain using the NITI model. This octahedral shear strain expansion provided a measure of the sensitivity of NITI parameter estimates. The method was investigated in numerical phantoms using NITI-based nonlinear inversion and applied to a brain study in a single subject with 10 repeat scans as well as 2 single scans from 5 different subjects. It was proposed that NITI–octahedral shear strain can also be used as a stability metric for anisotropic parameter reconstructions beyond nonlinear inversion.

2.9 | 3D single breath-hold MRE for the simultaneous assessment of liver fibrosis and inflammation in obese patients with NAFLD

2.9.1 | Presenter: Omar Isam Darwish, Kings College London, UK

MRE can measure fibrosis but is still limited in its sensitivity to hepatic inflammation. A novel rapid MRE acquisition sequence (Intenso-MRE) was used for the simultaneous acquisition of 2 slices combined with Hadamard encoding of full wave fields within a single breath-hold. Shear wave speed, storage modulus, loss modulus, and phase angel of the complex shear modulus of the liver of 9 patients with suspected nonalcoholic fatty liver disease (NAFLD) were computed. It was shown that the phase angle did not change with the inflammation score but decreased with fibrosis, and that shear wave speed correlated with the fibrosis score, whereas the loss modulus correlated with the inflammation score, providing a potentially sensitive marker of hepatic inflammation.

2.10 | Radial free-breathing liver MR elastography in children using self-navigation and rapid fractional encoding

2.10.1 | Presenter: Sevgi Gokce Kafali, University of California, Los Angeles, USA

Free-breathing acquisition is necessary for liver MRE in children and patients who cannot follow breathing commands. Integrating fractional encoding with self-navigation into a golden-angle radial gradient echo sequence might be a way to overcome these limitations. The feasibility of this approach was tested on healthy volunteers including children. Two image slices of the liver were acquired and compared with breath-hold MRE. It was concluded that a 60% acceptance rate generates better quality images with less signal deterioration than an 80% acceptance rate. Free-breathing and breath-hold techniques yielded similar liver stiffness values. Fractional encoding is beneficial to achieve a sufficiently high SNR in short T_2^* tissues.

2.11 | The influence of portal pressure on the tissue biophysical properties investigated in ex vivo rat livers

2.11.1 | Presenter: Yasmine Safraou, Charité Berlin, Germany

Interactions between liver stiffness and portal pressure were investigated in different scenarios of modulated matrix-vessel interactions in ex vivo rat livers. Multifrequency MRE, DWI, and T_2-weighted MRI were used, and automatic tissue segmentation was performed to investigate 4 different scenarios: livers embedded in soft gel (i); livers embedded in stiff gel to restrict liver expansion (ii); liver with reduced vascular compliance (iii); and liver with hydrophilic, that is, more viscous inflow solution (iv). It was found that as inflow pressure increased, water diffusivity increased in all scenarios, whereas liver stiffness decreased in all scenarios, except scenario (iv), indicating vascular leakage of low-viscosity fluid, which was also demonstrated histologically.

3 | KEYNOTE LECTURES (FRIDAY)

3.1 | Fast, high-resolution imaging methods for brain MR elastography by Curtis Johnson, University of Delaware, DE, USA

Due to the high heterogeneity of brain tissue, high-resolution MRE is essential for resolving the mechanical properties of neural tissue in vivo; however, this requirement poses challenges for solving the inverse problem of MRE. In his keynote lecture, Curtis Johnson presented nonlinear inversion as a physically rigorous approach to solving these problems and gave an overview on MRE sequences for cerebral applications. Nonlinear inversion based on wave data obtained with fast MRE sequences provides means for reproducible mapping of shear stiffness and damping ratio in the human brain in vivo. Short readout times, which can be achieved using segmented spiral MRE sequences in conjunction with phase correction navigator scans, yield MRE maps with an isotropic resolution of 1.5 mm within approximately 10 min.[2] Other state-of-the-art acquisition strategies have been proposed based on 3D multiband spin-echo MRE, a 3D hybrid radial-EPI readout scheme (TURBINE) MRE with 2.5 mm resolution,[3] or 3D spiral staircase MRE with 2 mm resolution[4] and can reduce scan time to less than 5 min. One of the issues that both MRE sequences and post-processing strategies have to deal with is motion-induced phase errors, which cause slice jitter in 2D single-shot sequences.[5] In MRE, there are different types of noise from physiological and vibration sources, all of which are correlated and should be adequately suppressed before wave inversion. MRE scans of the brain can be further accelerated by multicomponent acquisitions, though this comes at the cost of prolonged TE, or by undersampling the data, which preserves MRE information well up to rank 12.

3.2 | Cardiac MRE using intrinsic transient waves and wave dispersion by Ralph Sinkus, Kings College, London, UK

Aortic valve closure generates torsional and flexural waves in the left ventricle, which can be detected by MRE with high temporal resolution. Fast pencil-beam navigators could be used to track the propagation of torsional waves induced by aortic valve closure in the septum. Shear wave velocity was readily determined from the slope of wave fronts in waterfall diagrams in space and time. Stiffness of healthy myocardium was on the order of 36 kPa, whereas it was much higher in patients with heart failure with preserved ejection fraction. However, clinical applicability of this technique was found to be limited by challenges in positioning the pencil beam. Therefore, clinically robust 1D MRE scans were acquired within 8 breath-holds with pencil beams positioned perpendicular to the septum. The shear wave velocity measured in this way after correcting for myocardial thickness showed abnormally high stiffness in patients with myocardial amyloidosis. A similar concept based on transient punch actuation was applied in cardiac MRE in rats, allowing time-resolved stiffness measurements from systole to diastole. The second part of this keynote lecture addressed rheology in MRE, focusing on the spring-pot model. It was discussed that the spring-pot model does not match the phase angle of the complex shear modulus of liver tissue in vivo. MRE in tissues at different temperatures suggested shear wave scattering as a possible source of viscosity rather than thermal absorption. In this model, the modulus dispersion slope would be determined by the spatial fractality of the scatterers, whereas the ratio between storage and loss moduli would be determined by the viscoelastic matrix. Therefore, phase angle measurement in MRE could open many doors to the microvascular organization of tumors inferred from fractal scattering of shear waves.

3.3 | Application of MRE in brain diseases by Jens Würfel, Medical Image Analysis Center, Basel, Switzerland

Almost every pathology is associated with changes in biomechanical tissue properties. Typically, radiologists read contrast, that is, analyze the relative local changes in the images. This places MRE in the context of imaging techniques that can depict anatomy with high spatial resolution. Yet MRE, especially in the brain, is limited in its ability to provide the resolution necessary to detect gross anatomy at a scale of 2 mm isotropic resolution. In the discussion of the resolution that would be desirable for MRE in the future, an isotropic resolution of 1 mm has been proposed as a technical goal to detect details of brain stiffness similar to other state-of-the-art MRI techniques. Jens Würfel also asked what length scales determine the macroscopic signals detected by MRE. For example, the pathogenesis of multiple sclerosis involves many dynamic processes occurring simultaneously, from breakdown of the blood–brain barrier, activation of microglia, overshooting immune responses, anti-inflammatory signaling, iron deposition, and formation of perivascular lesions, to oligodendrocyte damage. All of these mechanisms can potentially alter the viscoelasticity of neural tissue to levels detectable by MRE. However, the specific mechanisms are still largely unknown. Demyelination clearly reduces brain stiffness, as shown in the cuprizone demyelination model in mice. Other mechanisms are more complex and difficult to decipher. In addition, this keynote lecture discussed relevant mechanisms potentially affecting MRE parameters, such as ECM remodeling, fluidity, invading metastases in neuro-oncology, edema, cellular infiltration, and remyelination in neuroinflammation; whereas rarefication, ECM degradation, debris, and beta-amyloid accumulation play a role in neurodegenerative diseases. A discussion of current challenges in neuroradiology, such as T_2 contrast-based characterization of MS lesions or grading of malignancies, highlights the perspectives to which MRE could contribute once challenges of homogenization and standardization have been resolved and methods for rapid and easy data reconstruction have become available.

3.4 | Multiparametric MRI of the kidney: Where does MRE fit in? by Steven P. Sourbron, University of Sheffield, UK

One of the major kidney functions is blood clearance. Therefore, the kidney is 1 of the most perfused organs in the body and is predominantly composed of tubular structures. The glomeruli filter out metabolites and waste products toward the tubules, but most of the filtrate is later reabsorbed by the peritubular capillary network. Steven Sourbron gave a comprehensive overview on the anatomy and function of the kidney in healthy and diseased individuals from a multiparametric MRI perspective with reference to the multicenter, EU-funded PARENCHIMA project.[6] He explained common etiologies of chronic kidney diseases (CKDs), which include diabetic, hypertensive, and atherosclerotic nephropathy, as well as glomerulonephritis such as lupus nephritis, Immunglobulin A nephropathy, and acute kidney injury. The end point of all CKD paths is dialysis and renal transplant. CKD affects 10% of the adult population with a trend toward an epidemic rise. CKDs progress silently until stage 4 or 5. Up to 30% of all CKD patients are diabetic, with kidneys constantly enlarging as they work under increased pressure. By measuring shear stiffness, MRE could provide surrogate markers of renal pressure to guide early prediction of renal failure and to determine the specific stage of the pathological cascade of pressure-related damage compensation in the kidney. Because renal biopsies are not attainable in all patients, the cause of CKD often remains unknown, posing challenges to diagnosis and management. With the advent of new therapies, it is becoming increasingly important to base management decisions on imaging findings. Here, MRI could be a game changer when performed multiparametrically, quantitatively, and specifically tailored to functional and structural elements in renal tissue. To include MRE in the renal multiparametric MRI protocol, it should be further standardized, simplified, and stabilized to provide off-the-shelf solutions that can be incorporated into future multiparametric MRI studies around the world.

3.5 | Advances in MR elastography: Its application in lung and aorta by Arunark Kolipaka, Ohio State University, Columbus, OH, USA

Lung function is classically assessed by spirometry, which is a good marker of lung function but does not provide information on lung structure and the underlying cause of lung dysfunction. In the first part of his keynote lecture, Arun Kolipaka outlined the challenges of lung MRE related to short T_2^*, low density of water protons, and motion artifacts due to respiration and cardiac motion. Single-shot spin-echo EPI is 1 way to overcome T_2^* problems in lung MRE. However, in lung MRE, it is necessary to consider the different respiratory states, which alter lung density. This has been demonstrated in healthy volunteers and in a bleomycin animal model of pulmonary fibrosis. Free-breathing lung MRE is feasible and suitable for clinical use, providing stiffness values averaged over the range of pulmonary densities occurring during the respiratory cycle. Reference values show that lung shear stiffness decreases with age without sex differences and were used for comparison with patients with interstitial lung disease and cystic fibrosis. The second part of this presentation focused on aortic MRE for mechanical assessment of rupture risk in patients with abdominal aortic aneurysm (AAA). Aortic MRE can measure shear waves in the lumen of the aorta based on waveguide effects. Cardiac-guided, free-breathing MRE with spin-echo EPI showed that AAA stiffness increased linearly with age and hypertension. Moreover, AAA stiffness was found to be significantly higher than that of the normal aorta, with each doubling of AAA stiffness associated with a 36% higher risk of AAA rupture.

3.6 | The potential role of cardiac MRE for improving women's health by Arvin Arani, Mayo Clinic, Rochester, MN, USA

Sex differences in cardiovascular disease are important to consider given the prevalence of sex disparities in the epidemiology of heart disease. Heart failure with preserved ejection fraction accounts for 50% of all cases of heart failure, and its incidence is twice as high in women than in men. In addition, menopause is associated with worse diastolic function and adverse left ventricular remodeling, and hormone therapies have exacerbated the problem in the past. Quantification of myocardial stiffness by cardiac MRE may play an important role in completing our understanding of sex-specific cardiovascular disease risk factors. Cardiac MRE shows that myocardial stiffness increases in women after age 50. In his lecture, Arvin Arani also pointed out the strong influence of diseases such as amyloid light chain cardiac amyloidosis on myocardial stiffness. A preliminary pilot study in patients with cardiac amyloidosis found that hematopoietic stem cell therapy significantly reduced left ventricular stiffness within 3 months of therapy. However, quantitative measures of myocardial stiffness are currently lacking for the phase of transition to menopause, a time frame when significant changes in stiffness can be expected and when therapies may be most effective. Future studies to understand these changes could play an important role in the management of heart failure in women and help reduce the sex differences that currently exist in the efficacy of cardiovascular therapies.

4 | PROFFERED PAPERS (FRIDAY)

4.1 | Decoupling prestress and waveguide effects from complex shear modulus estimates in a cylindrical structure using MRE

4.1.1 | Presenter: Dieter Klatt, University of Illinois Chicago, IL, USA

This presentation introduced a new method, transformation elastography, which is based on the idea of deforming space to make an anisotropic problem isotropic. The processing procedure was demonstrated using computational wave fields of a transversely isotropic cylinder and experimentally acquired wave fields of a fiber-reinforced anisotropic cylinder. Applying conventional isotropic inversion to transversely isotropic materials yields shear modulus values that fall between the true anisotropic values, whereas more accurate values are obtained using the transformation elastography approach. First, anisotropy was detected by the prominent peaks of wave intensity in k-space. This information was used to transform space to make the anisotropic problem isotropic. The technique was then modified to account for prestress in an isotropic material instead of for a preferred direction in an anisotropic scenario. It was found that both scenarios yielded transformation equations of a similar type, allowing differentiation of prestress-induced stiffening from intrinsic stiffening.

4.2 | Non-invasive in vivo quantification of water diffusion and biomechanical properties of the lower leg muscle in plantar and dorsiflexion using DTI and elastography

4.2.1 | Presenter: Mahsa Salimi Majd, Charité Berlin, Germany

Plantar flexion and dorsiflexion cause passive stretching and relaxation of the tibialis anterior and tibialis posterior/gastrocnemius muscle, respectively. Multifrequency MRE and DTI were performed in a group of healthy volunteers to investigate isotropic stiffness and TI material properties of these muscles. Muscle fiber alignment was determined by DTI tractography and used for incompressible 3-parameter direct inversion. In the tibialis anterior muscle, these investigations showed that, during dorsiflexion, shear modulus parallel to the muscle fibers was smaller than perpendicular shear modulus. This relationship of shear moduli changed toward the known property of a higher shear modulus parallel to the muscle fibers than perpendicular to them when the fibers were stretched during plantar flexion. Corresponding antagonistic properties were observed in the posterior tibialis.

4.3 | Investigating the effect of actuator number on multifrequency MRE (MMRE) of thigh muscle

4.3.1 | Presenter: Imogen Thrussell, The Institute of Cancer Research, London, UK

Quantitative MRI combined with MRE can be used to measure the response of soft tissue sarcoma in skeletal muscle to radiotherapy. However, tumor location varies among patients, requiring a reproducible MRE setup that covers the entire muscle. Therefore, use of multiple actuators is beneficial for shear wave excitation within larger areas and mapping stiffness throughout the muscle. The aim of the study presented here was to investigate whether multiple actuators affect MRE values or if the number of actuators affects the homogeneity of stiffness maps.

Nine healthy subjects were investigated with multifrequency MRE and different arrangements of up to 4 independent compressed air drivers. Direct inversion with only 1 actuator showed a significant signal drop, whereas wave number-based inversion showed stable values across all actuator configurations, even with only a single actuator.

5 | POSTER SESSION

A total of 19 posters were selected from the submitted abstracts, and they were all presented in traditional printed format. Poster visits and discussions took place during extended coffee and lunch breaks. The topics of the posters ranged from MRE technical development, numerical simulation, and phantom studies to preclinical and clinical applications. Lively discussions took place in a casual yet stimulating environment where ideas covering in-depth theory as well as practical experiment details were exchanged.

6 | PANEL DISCUSSION

On day 2, scientific lectures were followed by a lively panel discussion. Unlike originally planned, the panel discussion was not limited to a few members but extended to all attendees of the workshop. First, the winners of the student presentations were honored. Three MRE textbooks were awarded for the 2 best oral presentations and the best poster. The winners were selected by an anonymous online vote of all attendees. Yasmine Safraou from Charité Berlin and Siri Fløgstad Svensson from Oslo University Hospital were selected as the best talks. The poster prize was awarded to Anne-Sophie van Schelt from Amsterdam University Hospital. Congratulations to the winners! Following the prize ceremony, a few points regarding the activities of the MRE study group, standardization, and the possibility of launching an elastography journal were discussed. For standardization, there was a consensus that a challenge should be initiated in the MRE community to generate, collect, and evaluate the best and most reproducible MRE maps of the brain. This will require ground-truth data, as already published by Matt McGarry, Dartmouth College Hanover, NH, USA.[7] To overcome the challenge of correlated noise, it was proposed to include in vivo datasets as well. Further details will be discussed in the next virtual meeting of the study group, which will be held in November 2022. The idea of a journal for elastography was generally well received. MRE involves interdisciplinary research, which is currently covered only in a fragmented way in existing journals. In particular, the possibility of inviting other researchers working in different fields relevant to MRE, such as micromechanical testing methods or quantitative imaging in clinical trials, to publish in such a journal would greatly increase the visibility of MRE as a basic science method as well as a valuable imaging technique for clinical applications.

7 | CONCLUSION

In summary, this first MRE workshop organized by the ISMRM was a great success. It brought together many young scientists and established experts in MRE and from related fields and fostered a lively exchange of ideas, offered a broader perspective on MRE, and provided many practical insights, including hands-on exercises. After years of Covid-19, this on-site workshop was important to further shape an MRE community while advancing the important field of biomechanics-based MRI.

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