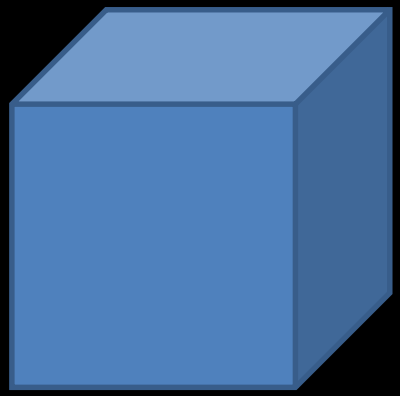
43ème CONGRÈS ANNUEL de la SFNR SOCIETE FRANCAISE DE NEURORADIOLOGIE
Du 30 mars au 1er avril 2016
Novotel Paris Tour Eiffel

Elastographie IRM Cérébrale

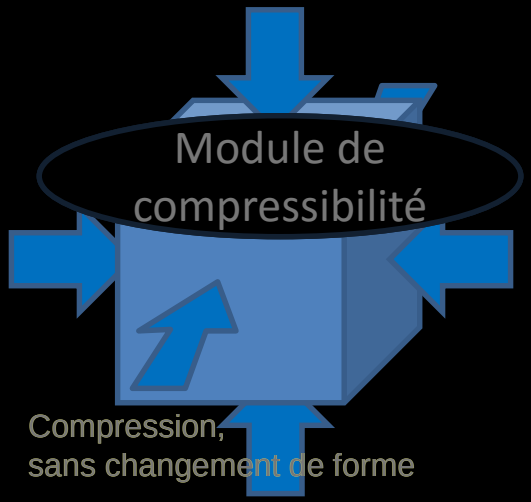
Inserm LabTAU

Rémi Souchon
INSERM, Lyon

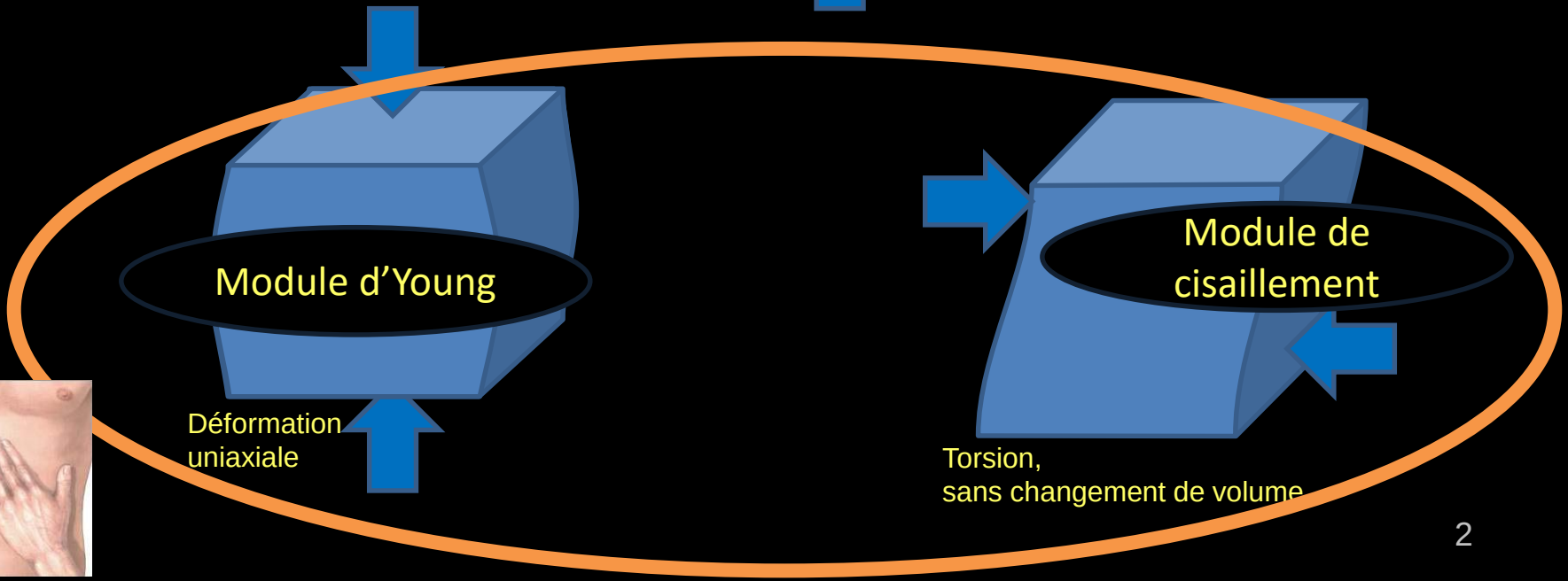
Comment mesurer l'élasticité ?



Au repos



Compression,
sans changement de forme



Déformation uniaxiale

Torsion,
sans changement de volume

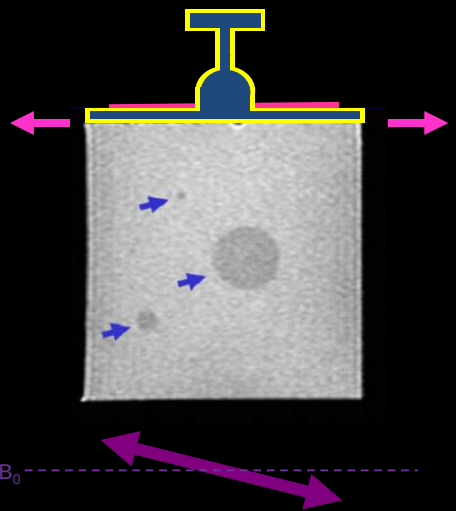
Ondes de cisaillement

Module de cisaillement = Densité x Vitesse de propagation de l'onde ^{2}

$$\mu = \rho c^2$$

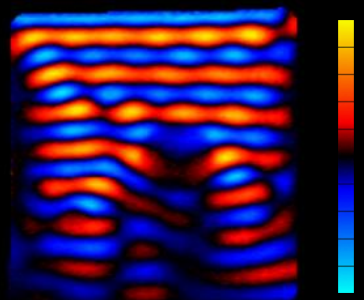
Elastographie IRM

Vibreur

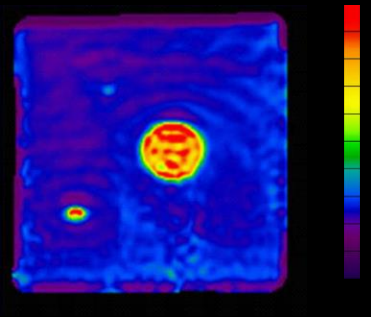


Champ magnétique oscillant
(« motion-encoding gradient »)

Images de phase
(déplacement)



Vitesse d'onde
(élasticité)

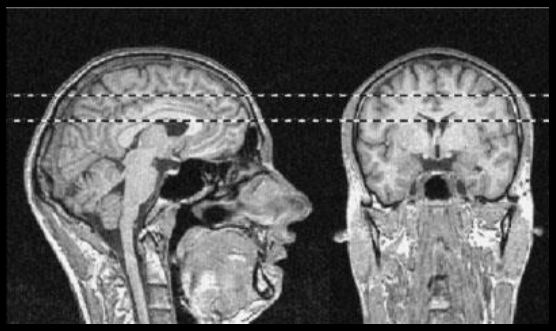


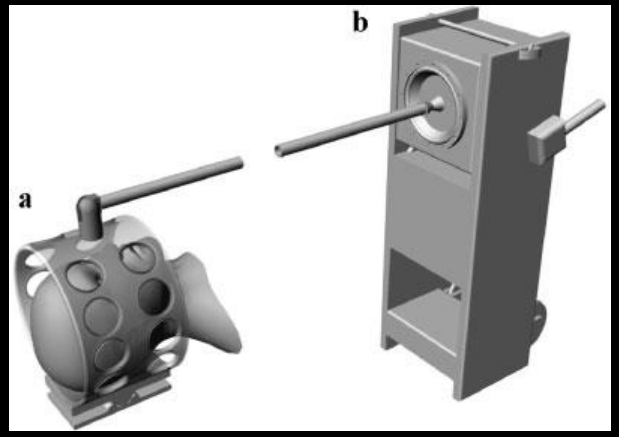
Magnetic Resonance Elastography by Direct Visualization of Propagating Acoustic Strain Waves

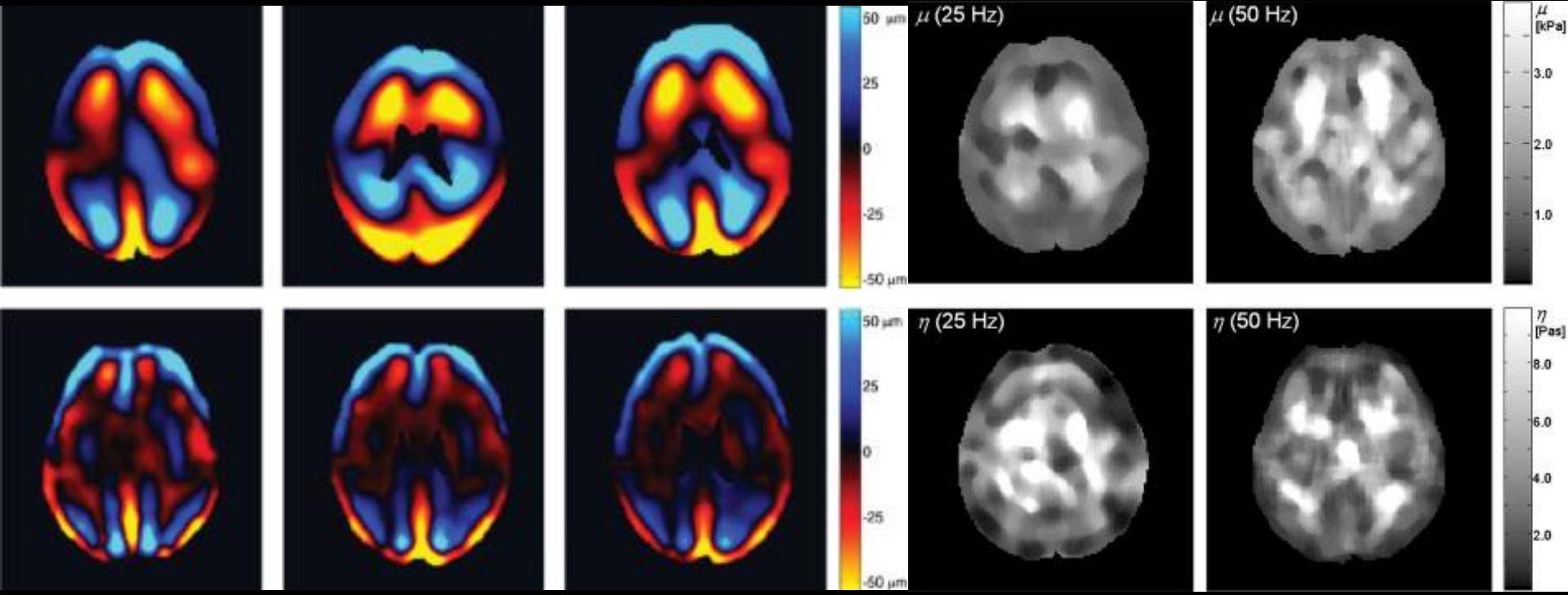
R. Muthupillai, D. J. Lomas, P. J. Rossman, J. F. Greenleaf, A. Manduca, R. L. Ehman*

SCIENCE • VOL. 269 • 29 SEPTEMBER 1995

Adapted from Pr. Ehman's slides
Mayo Clinic, Rochester MN, USA

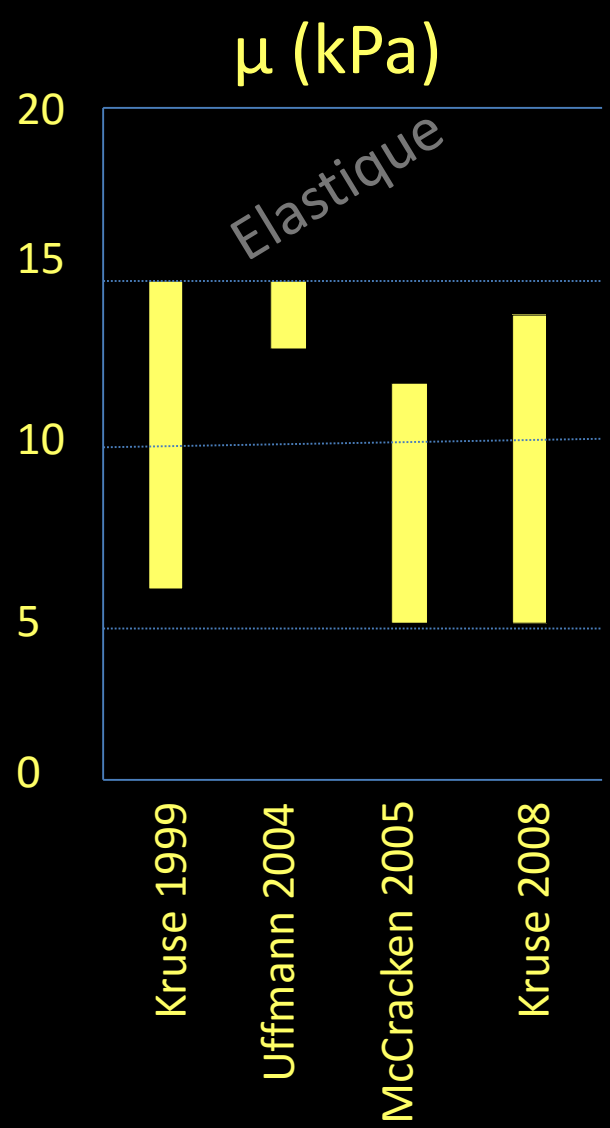


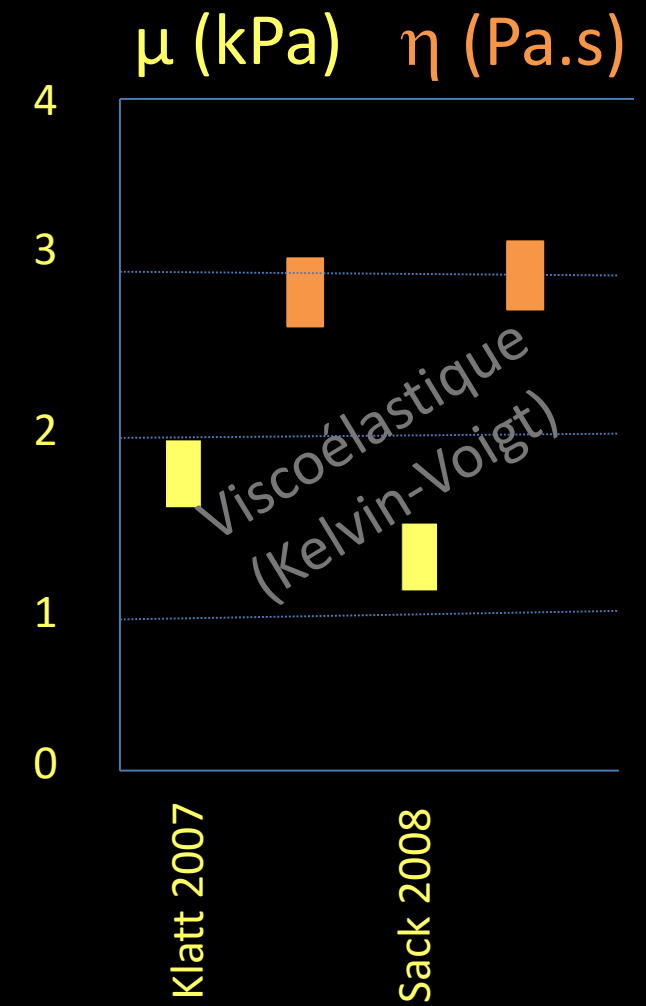


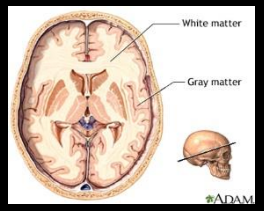


Sack I et al. Non-invasive measurement of brain viscoelasticity using magnetic resonance elastography. NMR Biomed. 2008; 21(3): 265-71.

Valeurs normales

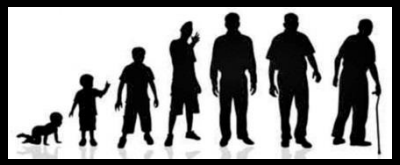






Matière blanche + dure

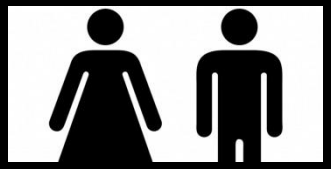
McCracken 2005
Kruse 2008



L'âg

-20% ent

Attention !
Etudes non comparables
car les modèles physiques
sont différents

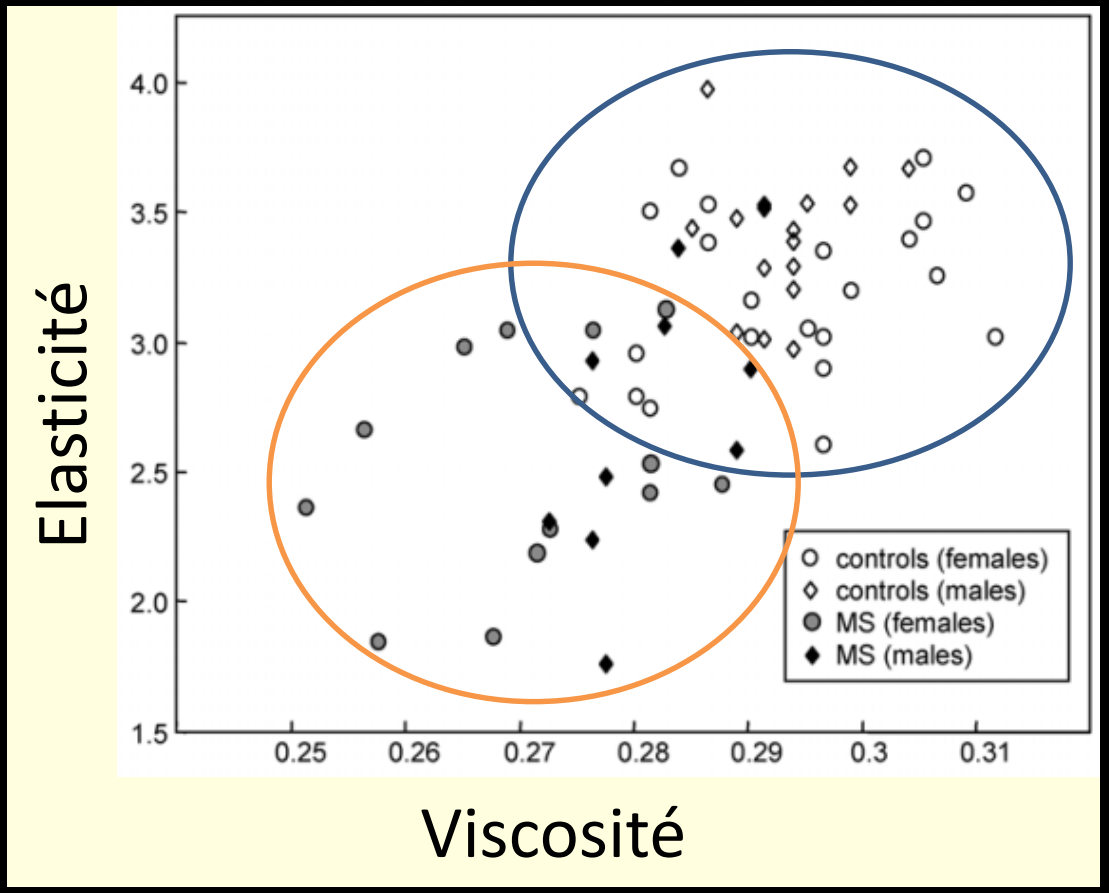


+ dur chez la femme

Wuerfel 2010

Sclérose en plaques

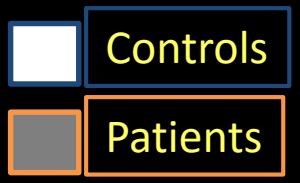
Formes progressives, chroniques



38 contrôles

23 patients

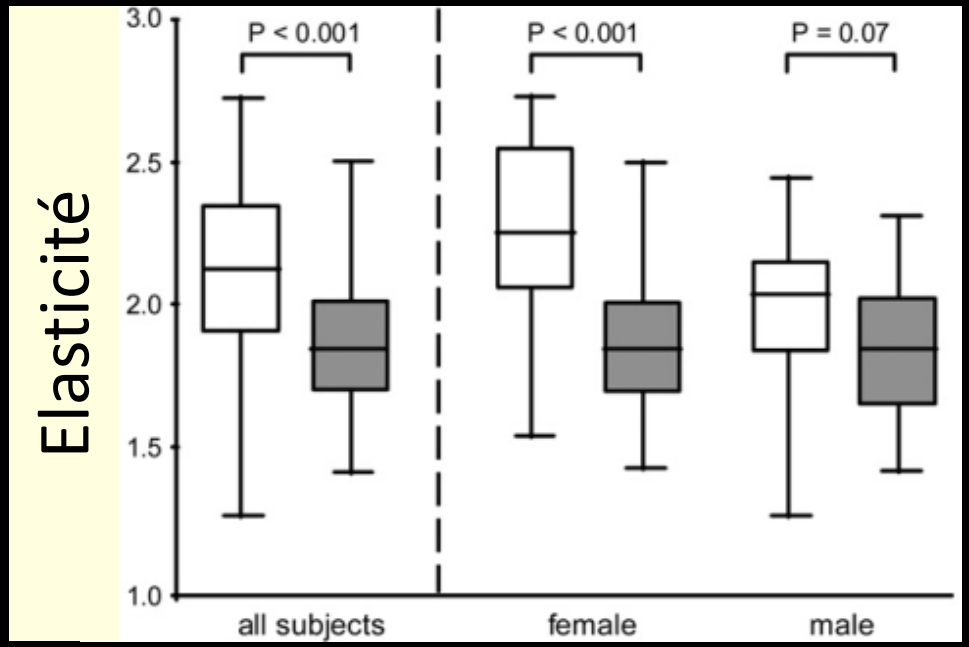
- EDSS 5.3-5.6



Streitberger KJ et al. Brain viscoelasticity alteration in chronic progressive multiple sclerosis. PlosOne 2012; 7(1): e29888

Sclérose en plaques

Formes modérées, rémittentes avec poussées



Patients (*N*=45)
Controls (*N*=34)

34 contrôles

45 patients

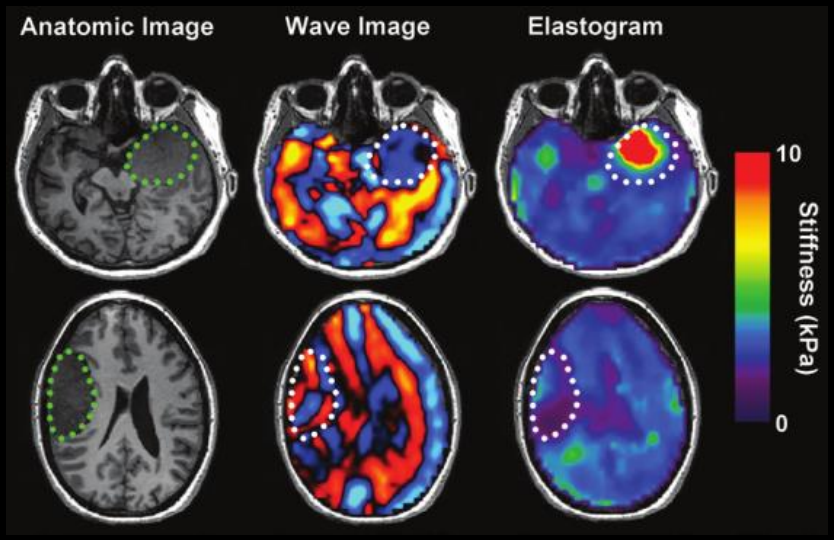
- EDSS 1.6 (0 – 4)
- Mild relapsing-remitting disease course

Elasticité

- Diminution 8-17%

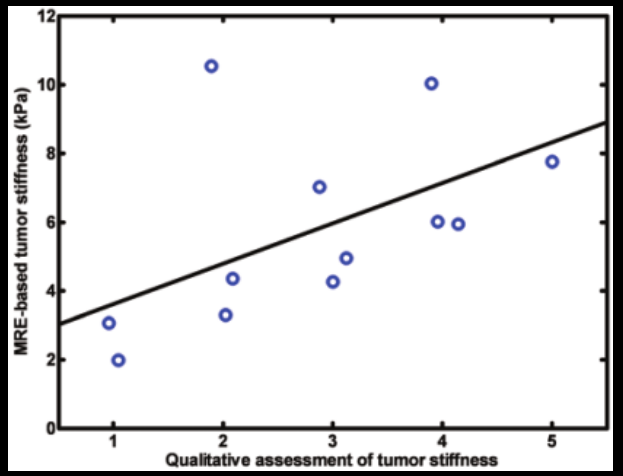
Wuerfel J et al. MR-elastography reveals degradation of tissue integrity in multiple sclerosis. NeuroImage 2010; 49: 2520-5

Méningiome



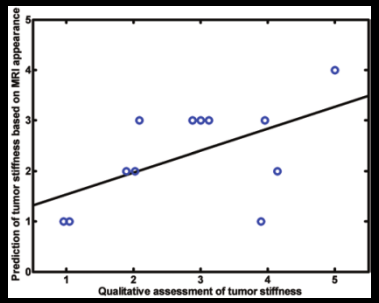
13 patients

Elasto



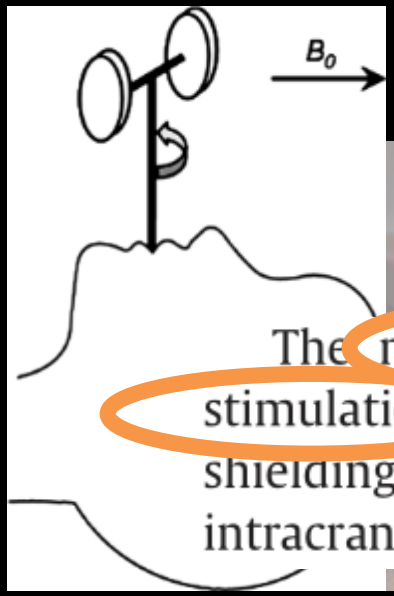
Palpation par chirurgien

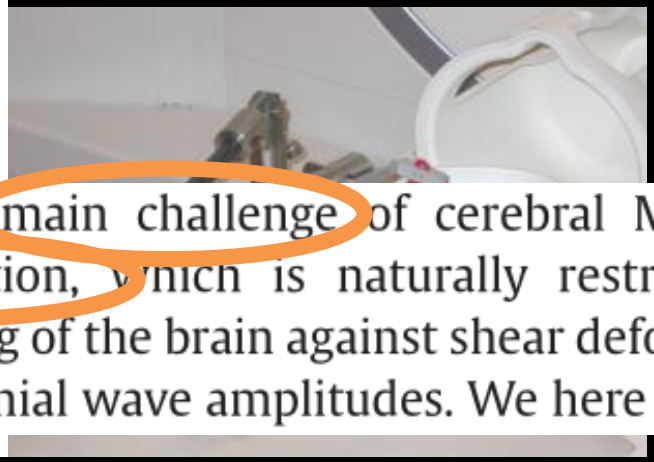
T1 & T2



Murphy MC et al. Preoperative assessment of meningioma stiffness using magnetic resonance elastography. J Neurosurg 2013; 118: 643-8

Vibreurs



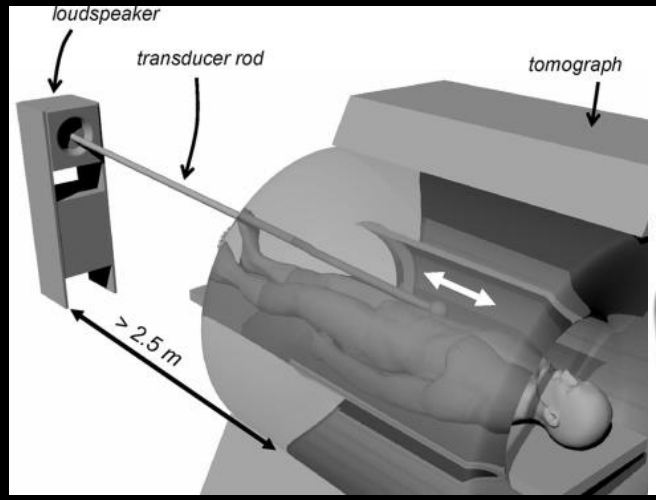


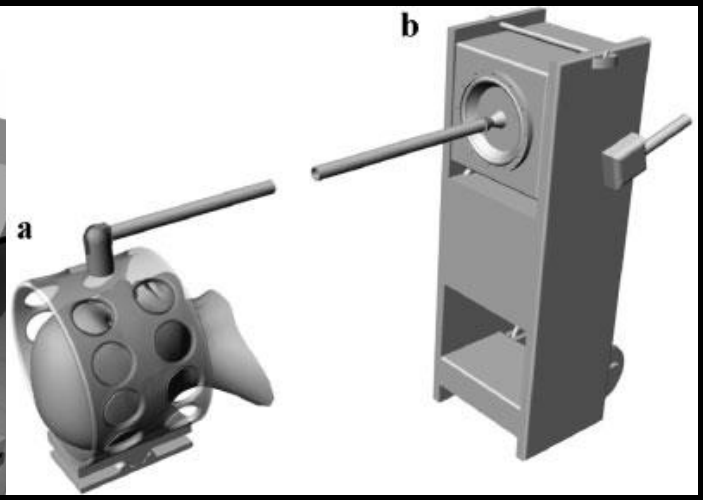
The main challenge of cerebral MRE is the mechanical brain stimulation, which is naturally restricted by the almost perfect shielding of the brain against shear deformations, hindering sufficient intracranial wave amplitudes. We here present a clinically applicable,

Wuerfel 2010

Mors

Bite bars

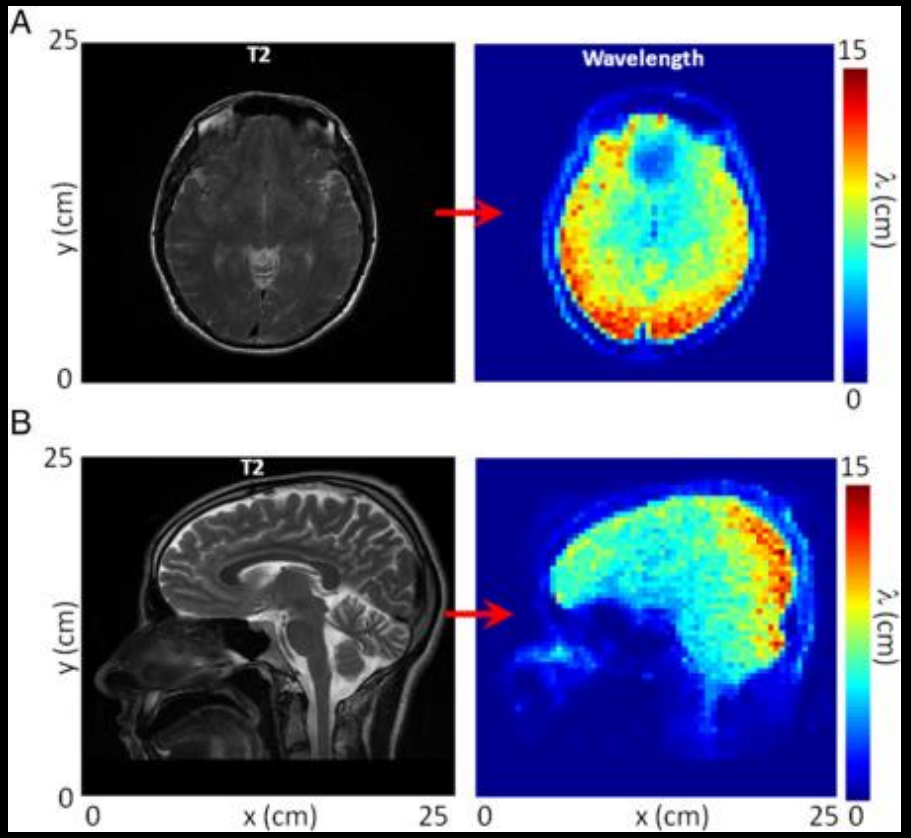




Haut-parleur + tige rigide

Loudspeaker + rigid rod

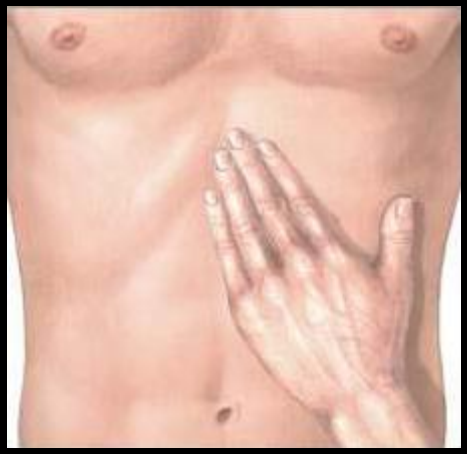
Elasto fonctionnelle, le futur ?

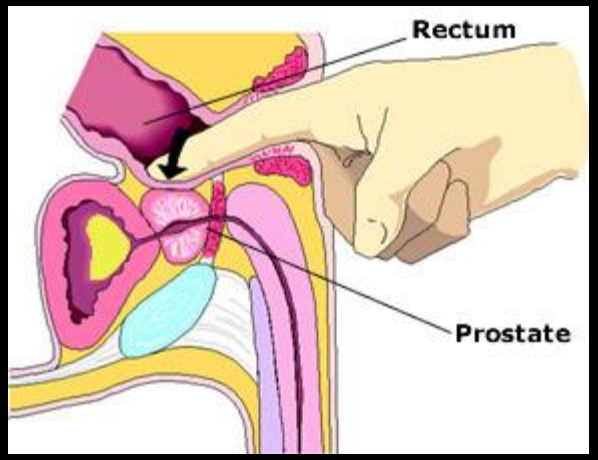


Zorgani A et al. Brain palpation from physiological vibrations using MRI. Proc Natl Acad Sci U S A. 2015; 112(42): 12917-21

Annexes

Elastographie – Imagerie d'élasticité





ELASTOGRAPHY: A QUANTITATIVE METHOD FOR IMAGING THE ELASTICITY OF BIOLOGICAL TISSUES

J. Ophir, I. Céspedes, H. Ponnekanti, Y. Yazdi and X. Li

ULTRASONIC IMAGING 13, 111-134 (1991)

Most illustrations from National Institutes of Health, USA

Feasibility

- Kruse 1999 – The first images
- Uffmann 2004
- McCracken 2005 – Transient
- Klatt 2007 – Zener, 25-60Hz
- Sack 2007 – Kelvin Voigt, 25-50Hz
- Kruse 2008
- Arani 2015 – Sex & Aging, shear modulus, 60Hz
- Zorgani 2015 – Physiological vibrations

Pathologies

- Sclérose en plaque
  - Wuerfel 2010: 45 patients, viscoelasticity decreased by 13% compared to healthy volunteers while structure-geometry remained unchanged, fractional springpot model, 25-60Hz
  - Streitberger 2012: chronic progressive multiple sclerosis, fractional springpot model, 25-60Hz
- Méningiome
  - Murphy 2013: shear modulus, 60Hz
  - Hughes 2015:

Etudes sur Animaux

- Jamin 2015 – Soft malignant tumors

Littérature (Kruse 2008)

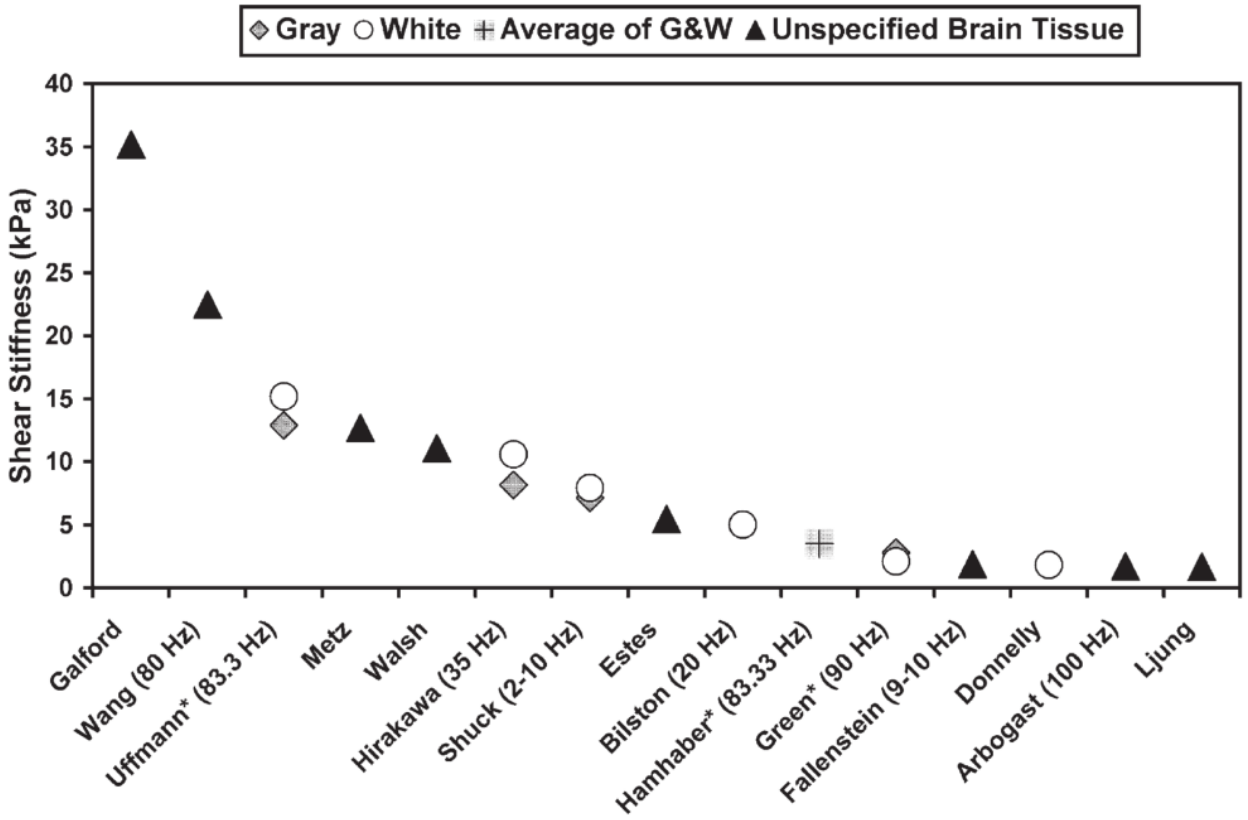
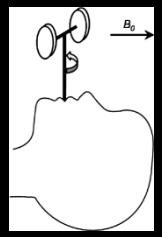


Fig. 1. Shear stiffness measurements in the literature of mammalian brain tissue (Arbogast and Margulies, 1998; Bilston et al., 1997; Donnelly and Medige, 1997; Estes and McElhaney, 1970; Fallenstein et al., 1969; Galford and McElhaney, 1970; Green et al., 2006; Hamhaber et al., 2007; Hirakawa et al., 1981; Ljung, 1975; Metz et al., 1970; Shuck and Advani, 1972; Uffmann et al., 2004; Walsh and Schettini, 1976; Wang and Wineman, 1972). The studies were performed *in vitro*, *ex vivo* and *in vivo* (denoted by *) using a variety of experimental techniques (shear/strain, load cell, pressure transducer, vibrating probe and MR elastography). The frequency of dynamic testing is indicated. The shear wave speed was calculated from the real and imaginary parts of the complex modulus (Auld, 1990; Oliphant et al., 2001). The result was then entered into Eq. (2) to calculate shear stiffness.

Modèles

- McCracken 2005 Elastic
- Klatt 2007 5 viscoelastic models
- Hamhaber 2007 Wave speed
- Kruse 2008 Elastic
- Sack 2008 Kelvin-Voigt



Kruse 1999

Rochester, MN, USA

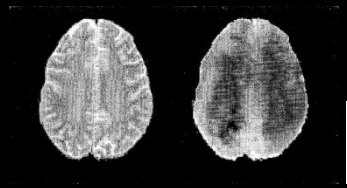


Figure 2. Left: T2 Weighted Spin Echo, Right: Local Frequency Estimate Map (Brain Compliance)

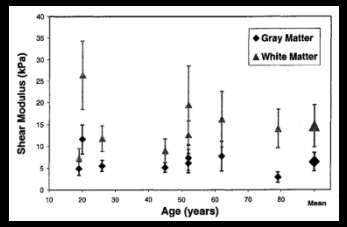


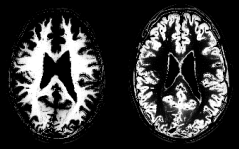
Figure 3. Elasticity Measurements of Cerebral Tissue *In Vivo*

Kruse SA et al. « Palpation of the brain » using magnetic resonance elastography. Proc ISMRM 1999

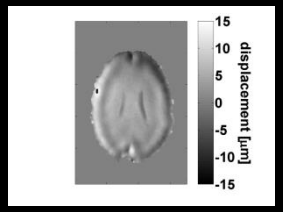
Uffmann 2004

Essen, Germany

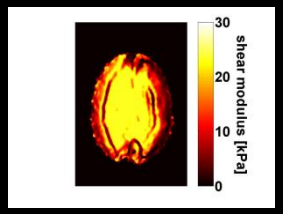
Bite bar



Probability map for white (left) and gray (right) matter

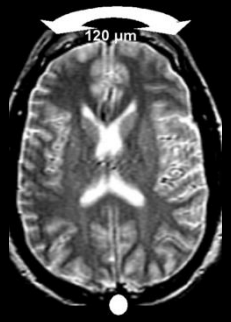


and white matter, respectively. The displacement due to the induced oscillation (Fig. 4) ranges from -15 to 15 µm. Fig. 5

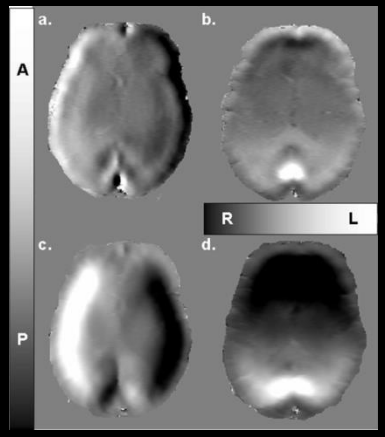


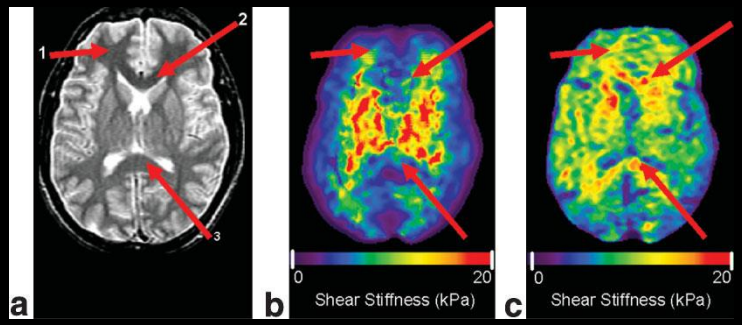
induced oscillation (Fig. 4) ranges from -15 to 15 µm. Fig. 5 shows an example of an elastogram reconstructed from a dataset consisting of eight phase images acquired with the same orientation but different phase offsets The elastogram shows artifacts where the displacement crosses zero.

Uffmann K et al. Determination of gray and white matter elasticity with MR elastography. Proc ISMRM 2004



McCracken 2005

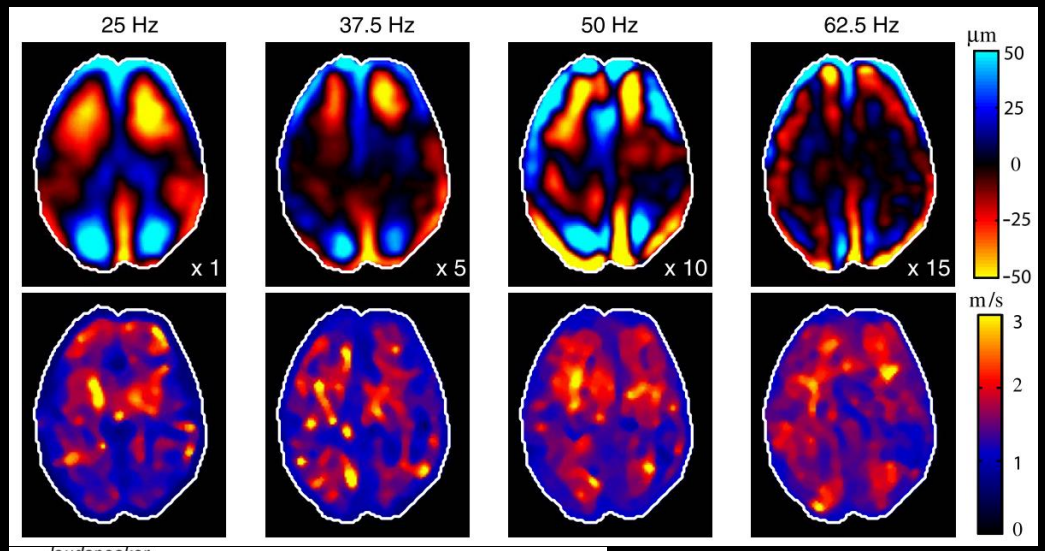


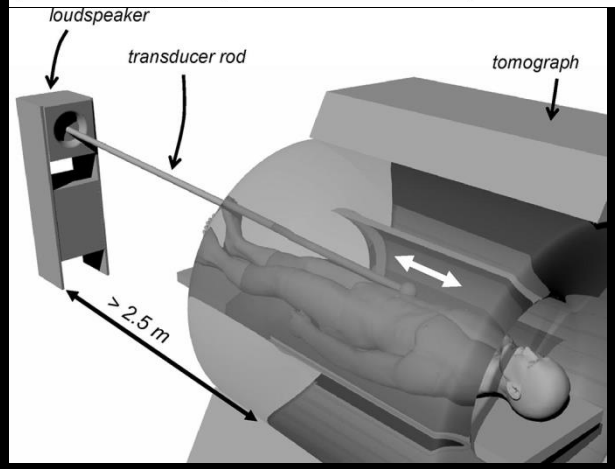


Magnetic resonance elastography (MRE) is a technique for quantifying material properties by measuring cyclic displacements of propagating shear waves. As an alternative to dynamic harmonic wave MRE or quasi-steady-state methods, the idea of using a transient impulse for mechanical excitation is introduced. Two processing methods to calculate shear stiffness from transient data were developed. The techniques were tested in phantom studies, and the transient results were found to be comparable to the harmonic wave results. Transient wave based analysis was applied to the brains of six healthy volunteers in order to assess the method in areas of complex wave patterns and geometry. The results demonstrated the feasibility of measuring brain stiffness in vivo using a transient mechanical excitation. Transient and harmonic methods both measure white matter (~12 kPa) to be stiffer than gray matter (~8 kPa). There were some anatomic differences between harmonic and transient MRE, specifically where the transient results better depicted the deeper structures of the brain. Magn Reson Med 53:628–639, 2005. © 2005 Wiley-Liss, Inc.

McCracken PJ et al. Mechanical transient-based magnetic resonance elastography. Magn Reson Med. 2005; 53(3): 628-39

Klatt 2007 – Viscoelastic models



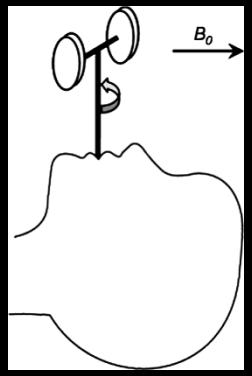


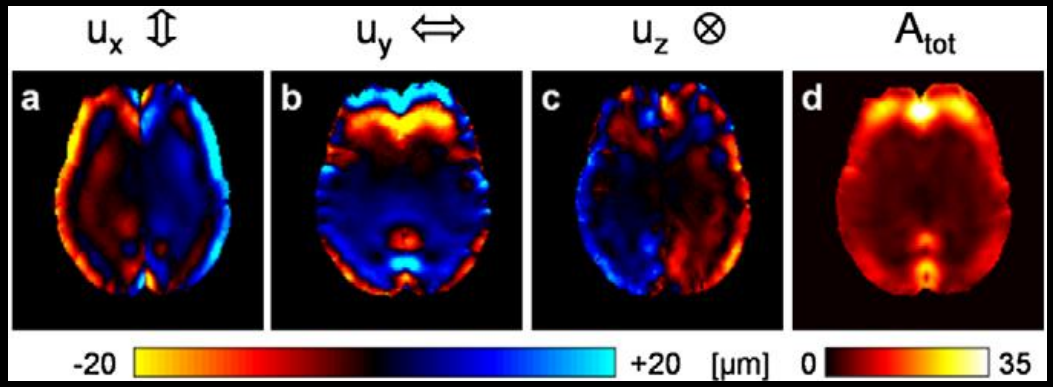
Abstract

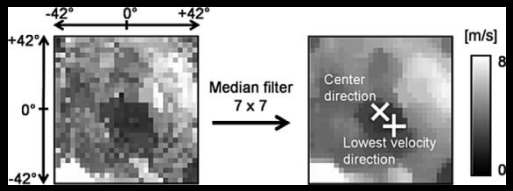
MR elastography (MRE) enables the noninvasive determination of the viscoelastic behavior of human internal organs based on their response to oscillatory shear stress. An experiment was developed that combines multifrequency shear wave actuation with broad-band motion sensitization to extend the dynamic range of a single MRE examination. With this strategy, multiple wave images corresponding to different driving frequencies are simultaneously received and can be analyzed by evaluating the dispersion of the complex modulus over frequency. The technique was applied on the brain and liver of five healthy volunteers. Its repeatability was tested by four follow-up studies in each volunteer. Five standard rheological models (Maxwell, Voigt, Zener, Jeffreys and fractional Zener model) were assessed for their ability to reproduce the observed dispersion curves. The three-parameter Zener model was found to yield the most consistent results with two shear moduli $\mu_1 = 0.84 \pm 0.22$ (1.36 ± 0.31) kPa, $\mu_2 = 2.03 \pm 0.19$ (1.86 ± 0.34) kPa and one shear viscosity of $\eta = 6.7 \pm 1.3$ (5.5 ± 1.6) Pa s (interindividual mean ± SD) in brain (liver) experiments. Significant differences between the rheological parameters of brain and liver were found for μ_1 and η ($P < 0.05$), indicating that human brain is softer and possesses a higher viscosity than liver.

Klatt D et al. Noninvasive assessment of the rheological behavior of human organs using multifrequency MR elastography: a study of brain and liver viscoelasticity. Phys Med Biol. 2007; 52(24): 7281-94

Hamhaber 2007







Abstract

Dynamic magnetic resonance elastography (MRE) is a non-invasive method for the quantitative determination of the mechanical properties of soft tissues *in vivo*. In MRE, shear waves are generated in the tissue and visualized using phase-sensitive MR imaging methods. The resulting two-dimensional (2-D) wave images can reveal in-plane elastic properties when possible geometrical biases of the wave patterns are taken into account. In this study, 3-D MRE experiments of *in vivo* human brain are analyzed to gain knowledge about the direction of wave propagation and to deduce in-plane elastic properties. The direction of wave propagation was determined using a new algorithm which identifies minimal wave velocities along rays from the surface into the brain. It was possible to quantify biases of the elastic parameters due to projections onto coronal, sagittal and transversal image planes in 2-D MRE. It was found that the in-plane shear modulus is increasingly overestimated when the image slice is displaced from narrow slabs of 2–5 cm through the center of the brain. The mean shear modulus of the brain was deduced from 4-D wave data with about 3.5 kPa. Using the proposed slice positions in 2-D MRE, this shear modulus can be reproduced with an acceptable error within a fraction of the full 3-D examination time.

Kruse 2008

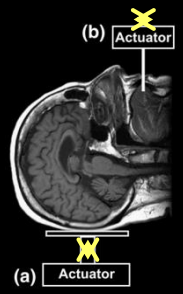


Fig. 2. Schematic diagram of the magnetic resonance elastography system. Conventional MR imaging gradients and RF pulses that encode spatial positions are shown at the bottom left. The electromechanical actuator (a) applies vertical displacement to the object to be imaged via a cradle or (b) horizontal displacement via a bite block (right). The cyclic motion-sensitizing gradients and the actuator are synchronized using trigger pulses provided by the imager. The phase offset (θ) between the two can be varied to image the waves at various stages of propagation. As shown by the shaded regions, the motion-sensitizing gradients can be superimposed along any desired axis to detect that component of the cyclic motion vector. All data was collected and analyzed using 100 Hz motion.

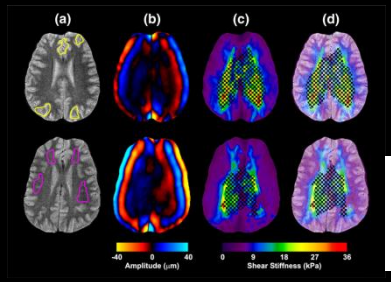


Fig. 4. Results from the MRE experiment performed on 2 different volunteers aged 25 and 23 using 100-Hz mechanical excitations. (a) T2-weighted FSE images for anatomical reference. The ROIs for gray matter and white matter are indicated in the top and bottom rows respectively. (b) Images indicating the shear waves propagating in the brain. The shear waves propagate from the perimeter of the brain inward. (c) The shear stiffness maps computed from the local frequency estimate (LFE) algorithm. A threshold, based on a phase difference SNR of 5:1, was applied to the shear stiffness estimates to mask regions with low displacement amplitude. (d) The shear stiffness maps overlaid on the anatomical reference illustrate the correlation of stiffness changes to anatomy.

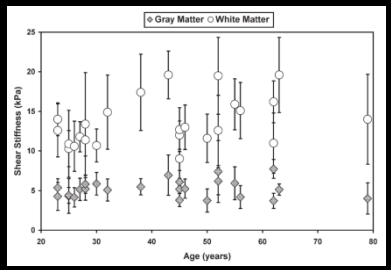
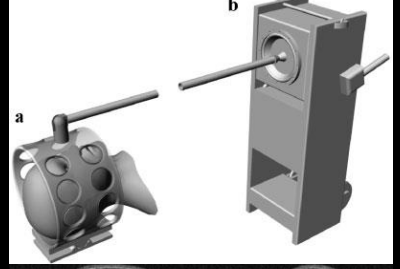


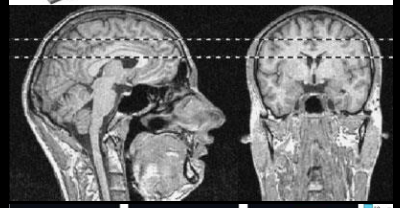
Fig. 5. Shear stiffness measurements for the age study volunteers obtained at 100 Hz.

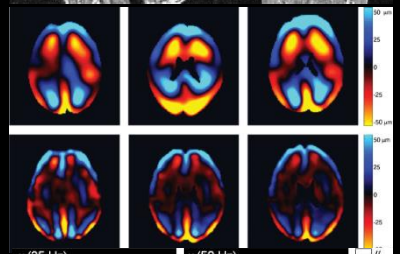
The purpose of this study was to obtain normative data using magnetic resonance elastography (MRE) (a) to obtain estimates of the shear modulus of human cerebral tissue *in vivo* and (b) to assess a possible age dependence of the shear modulus of cerebral tissue in healthy adult volunteers. MR elastography studies were performed on tissue-simulating gelatin phantoms and 25 healthy adult volunteers. The data were analyzed using spatiotemporal filters and a local frequency estimating algorithm. Statistical analysis was performed using a paired *t*-test. The mean shear stiffness of cerebral white matter was 13.6 kPa (95% CI 12.3 to 14.8 kPa); while that of gray matter was lower at 5.22 kPa (95% CI 4.76 to 5.66 kPa). The difference was statistically significant ($p < 0.0001$).

Kruse SA et al. Magnetic resonance elastography of the brain. Neuroimage. 2008; 39(1): 231-7.

Sack 2008







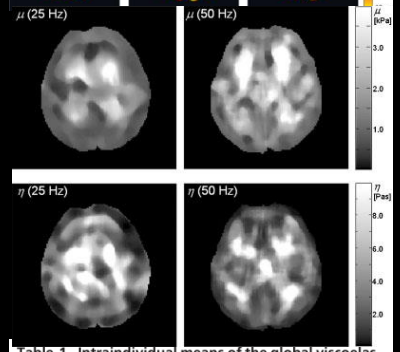


Table 1. Intraindividual means of the global viscoelastic data for volunteers 1–6 and corresponding interindividual average at 25 Hz and 50 Hz mechanical excitation frequencies. The error tolerances (±) are given as standard deviations

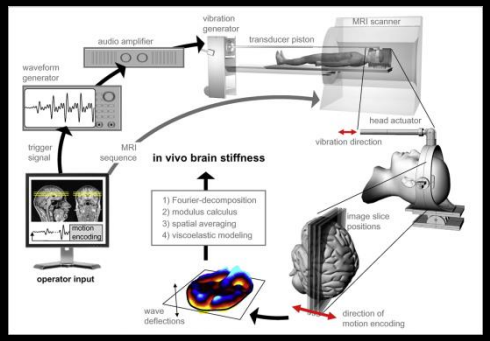
	μ (kPa)		η (Pas)	
Volunteer	25 Hz	50 Hz	25 Hz	50 Hz
1	1.17 ± 0.04	1.56 ± 0.1	3.5 ± 0.2	3.3 ± 0.2
2	1.19 ± 0.04	1.54 ± 0.12	2.8 ± 0.5	3.4 ± 0.4
3	1.16 ± 0.06	1.45 ± 0.06	3.8 ± 0.5	3.3 ± 0.2
4	1.19 ± 0.05	1.54 ± 0.13	3.1 ± 0.5	3.2 ± 0.4
5	1.2 ± 0.05	1.61 ± 0.06	3.0 ± 0.3	3.7 ± 0.2
6	1.12 ± 0.07	1.64 ± 0.11	2.6 ± 0.4	3.7 ± 0.3
1–6	1.17 ± 0.03[a]	1.56 ± 0.07[a]	3.1 ± 0.4[a]	3.4 ± 0.2[a]

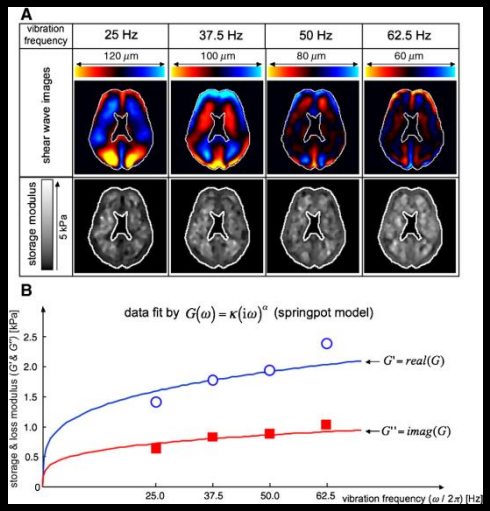
[a]Here, standard deviations correspond to confidence intervals with $P \leq 0.01$.

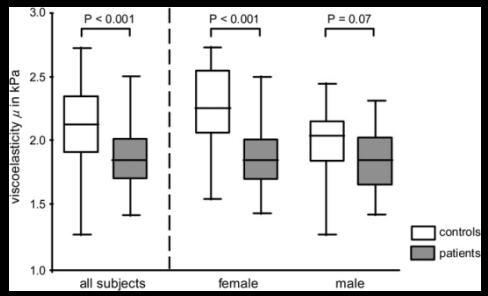
ABSTRACT: The purpose of this work was to develop magnetic resonance elastography (MRE) for the fast and reproducible measurement of spatially averaged viscoelastic constants of living human brain. The technique was based on a phase-sensitive echo planar imaging acquisition. Motion encoding was orthogonal to the image plane and synchronized to intracranial shear vibrations at driving frequencies of 25 and 50 Hz induced by a head-rocker actuator. Ten time-resolved phase-difference wave images were recorded within 60 s and analyzed for shear stiffness and shear viscosity. Six healthy volunteers (six men; mean age 34.5 years; age range 25–44 years) underwent 23–39 follow-up MRE studies over a period of 6 months. Interindividual mean ± SD shear moduli and shear viscosities were found to be 1.17 ± 0.03 kPa and 3.1 ± 0.4 Pas for 25 Hz and 1.56 ± 0.07 kPa and 3.4 ± 0.2 Pas for 50 Hz, respectively ($P \leq 0.01$). The intraindividual range of shear modulus data was 1.01–1.31 kPa (25 Hz) and 1.33–1.77 kPa (50 Hz). The observed modulus dispersion indicates a limited applicability of Voigt's model to explain viscoelastic behavior of brain parenchyma within the applied frequency range. The narrow distribution of data within small confidence intervals demonstrates excellent reproducibility of the experimental protocol. The results are necessary as reference data for future comparisons between healthy and pathological human brain viscoelastic data.

Sack I et al. Non-invasive measurement of brain viscoelasticity using magnetic resonance elastography. NMR Biomed. 2008; 21(3): 265-71.

Wuerfel 2010





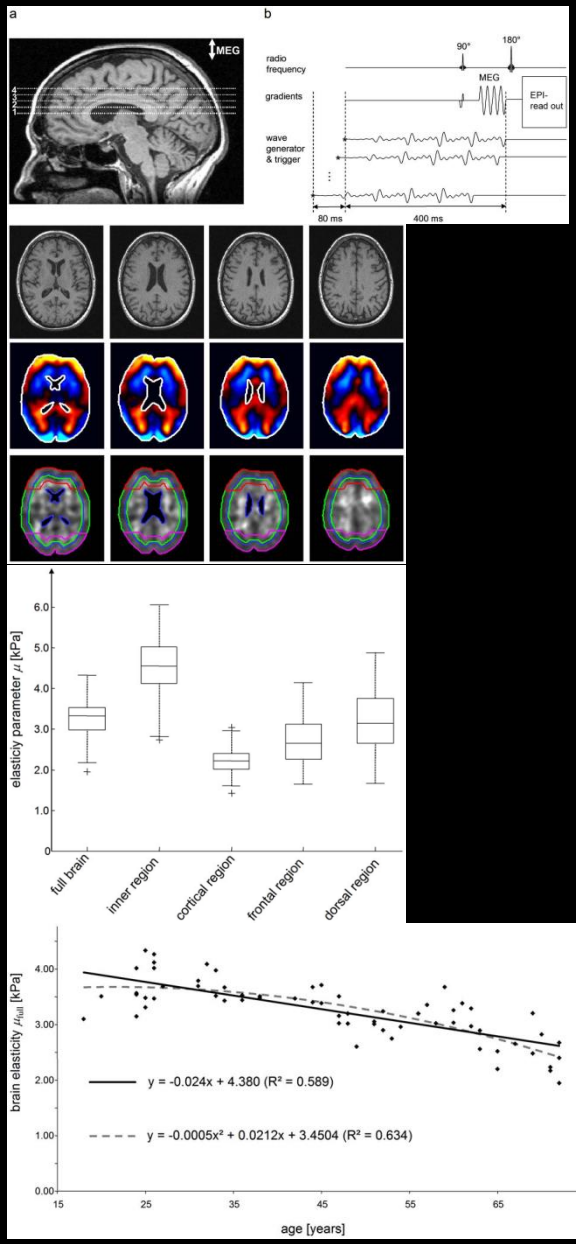


A B S T R A C T

In multiple sclerosis (MS), diffuse brain parenchymal damage exceeding focal inflammation is increasingly recognized to be present from the very onset of the disease, and, although occult to conventional imaging techniques, may present a major cause of permanent neurological disability. Subtle tissue alterations significantly influence biomechanical properties given by stiffness and internal friction, that – in more accessible organs than the brain – are traditionally assessed by manual palpation during the clinical exam. The brain, however, is protected from our sense of touch, and thus our current knowledge on cerebral viscoelasticity is very limited. We developed a clinically feasible magnetic resonance elastography setup sensitive to subtle alterations of brain parenchymal biomechanical properties. Investigating 45 MS patients revealed a significant decrease (13%, $P<0.001$) of cerebral viscoelasticity compared to matched healthy volunteers, indicating a widespread tissue integrity degradation, while structure-geometry defining parameters remained unchanged. Cerebral viscoelasticity may represent a novel *in vivo* marker of neuroinflammatory and neurodegenerative pathology.

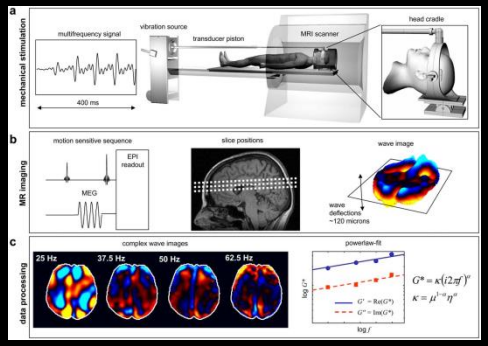
Wuerfel J et al. MR-elastography reveals degradation of tissue integrity in multiple sclerosis. NeuroImage 2010; 49: 2520-5

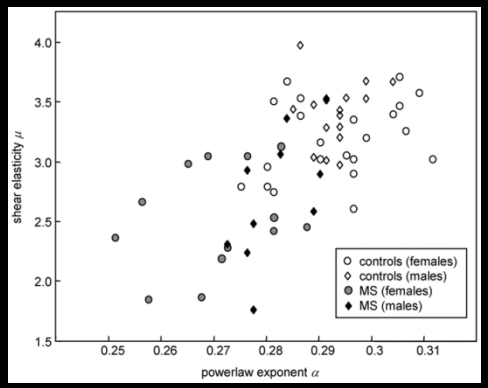
Sack 2011

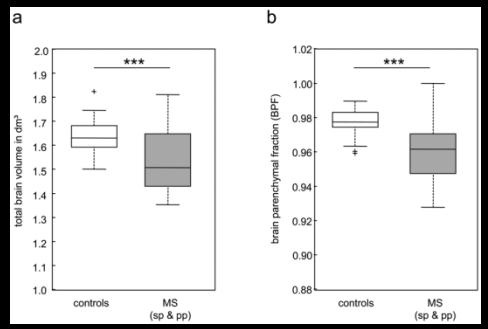


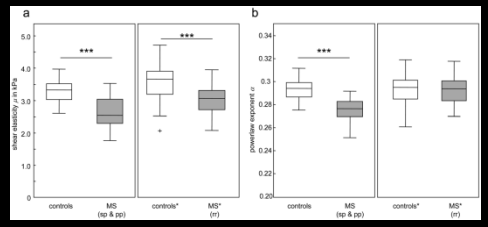
Sack I et al. The influence of physiological aging and atrophy on brain viscoelastic properties in humans. PLoS One 2011; 6(9): e23451

Streitberger 2012









Abstract

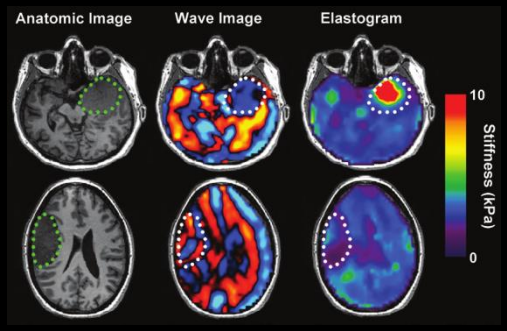
Introduction: Viscoelastic properties indicate structural alterations in biological tissues at multiple scales with high sensitivity. Magnetic Resonance Elastography (MRE) is a novel technique that directly visualizes and quantitatively measures biomechanical tissue properties *in vivo*. MRE recently revealed that early relapsing-remitting multiple sclerosis (MS) is associated with a global decrease of the cerebral mechanical integrity. This study addresses MRE and MR volumetry in chronic-progressive disease courses of MS.

Methods: We determined viscoelastic parameters of the brain parenchyma in 23 MS patients with primary or secondary chronic progressive disease course in comparison to 38 age- and gender-matched healthy individuals by multifrequency MRE, and correlated the results with clinical data, T2 lesion load and brain volume. Two viscoelastic parameters, the shear elasticity μ and the powerlaw exponent α, were deduced according to the springpot model and compared to literature values of relapsing-remitting MS.

Results: In chronic-progressive MS patients, μ and α were reduced by 20.5% and 6.1%, respectively, compared to healthy controls. MR volumetry yielded a weaker correlation: Total brain volume loss in MS patients was in the range of 7.5% and 1.7% considering the brain parenchymal fraction. All findings were significant ($P<0.001$).

Conclusions: Chronic-progressive MS disease courses show a pronounced reduction of the cerebral shear elasticity compared to early relapsing-remitting disease. The powerlaw exponent α decreased only in the chronic-progressive stage of MS, suggesting an alteration in the geometry of the cerebral mechanical network due to chronic neuroinflammation.

Streitberger KJ et al. Brain viscoelasticity alteration in chronic progressive multiple sclerosis. PlosOne 2012; 7(1): e29888



Murphy 2013

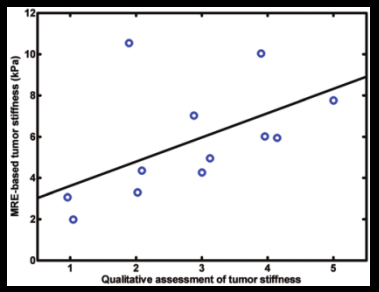


Fig. 2. Plot showing tumor stiffness as measured by MRE versus the surgeons' qualitative assessment of tumor stiffness (r = 0.65, p = 0.023). Scatter along the x axis is random and for display purposes only to avoid overlapping data points.

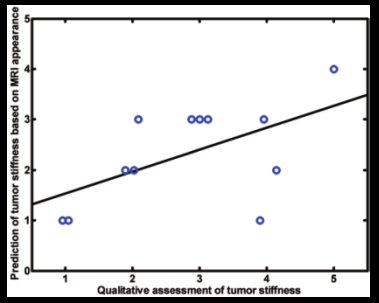


Fig. 4. Plot showing MRI (T1- and T2-weighted imaging) prediction of tumor stiffness versus the surgeons' qualitative assessment of tumor stiffness (r = 0.51, p = 0.089). Scatter along the x axis is random and for display purposes only to avoid overlapping data points.

Object. The object of this study was to determine the potential of magnetic resonance elastography (MRE) to preoperatively assess the stiffness of meningiomas.

Methods. Thirteen patients with meningiomas underwent 3D brain MRE examination to measure stiffness in the tumor as well as in surrounding brain tissue. Blinded to the MRE results, neurosurgeons made a qualitative assessment of tumor stiffness at the time of resection. The ability of MRE to predict the surgical assessment of stiffness was tested using a Spearman rank correlation.

Results. One case was excluded due to a small tumor size. In the remaining 12 cases, both tumor stiffness alone (p = 0.023) and the ratio of tumor stiffness to surrounding brain tissue stiffness (p = 0.0032) significantly correlated with the surgeons' qualitative assessment of tumor stiffness. Results of the MRE examination provided a stronger correlation with the surgical assessment of stiffness compared with traditional T1- and T2-weighted imaging (p = 0.089), particularly when considering meningiomas of intermediate stiffness.

Conclusions. In this cohort, preoperative MRE predicted tumor consistency at the time of surgery. Tumor stiffness as measured using MRE outperformed conventional MRI because tumor appearance on T1- and T2-weighted images could only accurately predict the softest and hardest meningiomas.

Murphy MC et al. Preoperative assessment of meningioma stiffness using magnetic resonance elastography. J Neurosurg 2013; 118: 643-8

Jamin 2015 - Mice

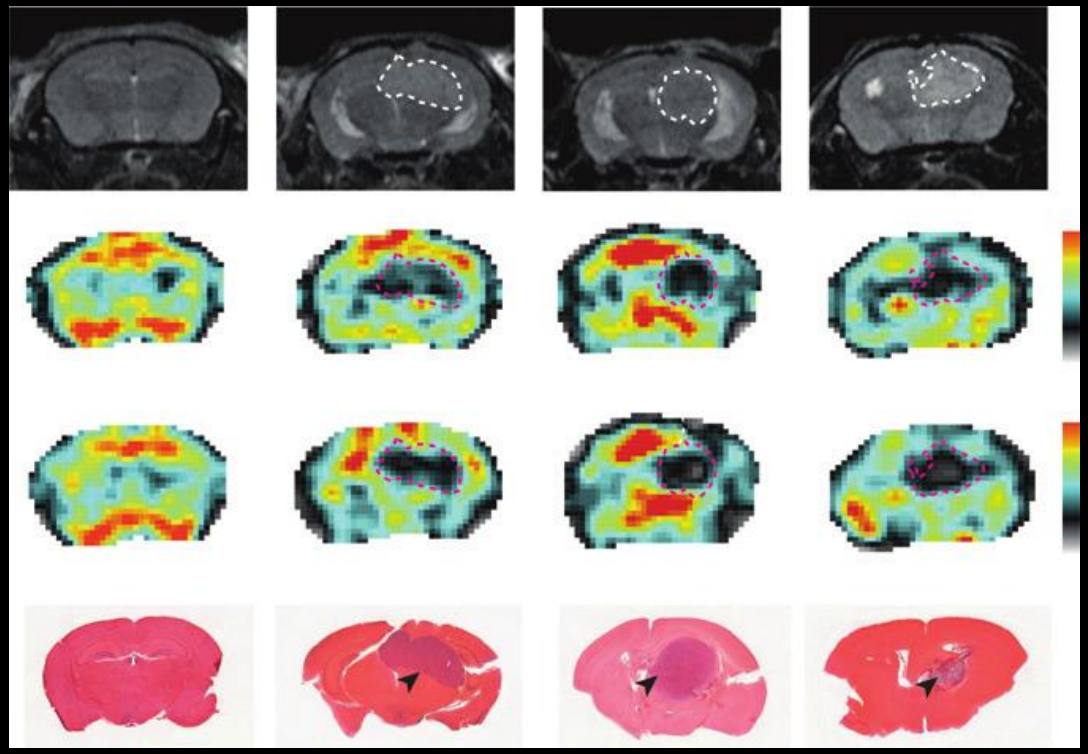


Figure 1.
Noninvasive imaging of the viscoelastic properties of intracranial tumors assessed by MRE. Anatomical T_2-weighted MR images, and parametric maps of elasticity (G_d) and viscosity (G_l) acquired from a non–tumor-bearing mouse, and mice bearing tumors derived from human adult U-87 MG glioblastoma, *N*-ethyl-*N*-nitrosourea–induced RG2 rat glioma, or human triple-negative MDA-MB-231 breast carcinoma cells are shown. —, tumor boundaries defined on T_2-weighted images. Images of whole H&E–stained sections obtained from the same mice are also shown, with the tumor location arrowed.

Malignant tumors are typically associated with altered rigidity relative to normal host tissue. Magnetic resonance elastography (MRE) enables the noninvasive quantitation of the mechanical properties of deep-seated tissue following application of an external vibrational mechanical stress to that tissue. In this preclinical study, we used MRE to quantify (kPa) the elasticity modulus G_d and viscosity modulus G_l of three intracranially implanted glioma and breast metastatic tumor models. In all these brain tumors, we found a notable softness characterized by lower elasticity and viscosity than normal brain parenchyma, enabling their detection on G_d and G_l parametric maps. The most circumscribed tumor (U-87 MG glioma) was the stiffest, whereas the most infiltrative tumor (MDA-MB-231 metastatic breast carcinoma) was the softest. Tumor cell density and microvessel density correlated significantly and positively with elasticity and viscosity, whereas there was no association with the extent of collagen deposition or myelin fiber entrapment. In conclusion, although malignant tumors tend to exhibit increased rigidity, intracranial tumors presented as remarkably softer than normal brain parenchyma. Our findings reinforce the case for MRE use in diagnosing and staging brain malignancies, based on the association of different tumor phenotypes with different mechanical properties.
Cancer Res; 75(7); 1216–24.

Hughes 2015

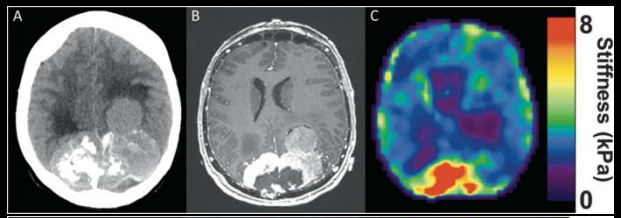


FIGURE 1. *A, computed tomography of the head showing a large parietooccipital parasagittal meningioma with a nodule of tumor on the left extending farther anteriorly. The right side of the tumor is calcified.* **B**, *T1-weighted magnetic resonance imaging with contrast defines the tumor further.* **C**, *magnetic resonance elastography shows that the tumor is heterogeneous with the posterior portion being hard and the more left lateral and anterior nodule becoming progressively softer. Intraoperatively, the posterior region of the tumor had to be removed with heavy scissors, but as the dissection moved to the left and anteriorly, the tumor was easily removed with the ultrasonic aspirator at low settings.*

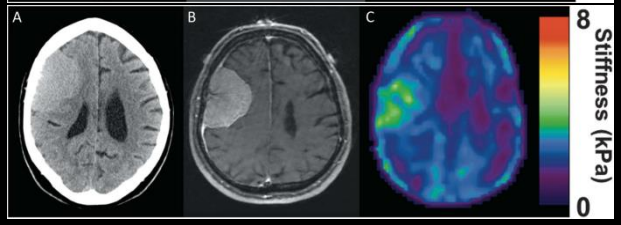


FIGURE 2. *A, computed tomography of the head showing an isodense right frontal convexity tumor.* **B**, *T1-weighted magnetic resonance imaging with contrast shows a homogeneously enhancing tumor consistent with meningioma.* **C**, *magnetic resonance elastography (MRE) shows a soft homogeneous tumor. Intraoperatively, the tumor was easily removed with ultrasonic aspirator and was consistent throughout.*

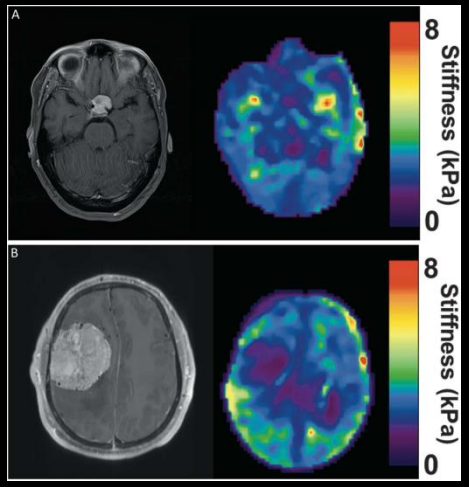


FIGURE 5. *Examples of tumors that did not correlate well with magnetic resonance elastography (MRE) and surgical findings.* **A**, *a small planum sphenoidale meningioma that measured 2.2 cm in maximum diameter. MRE showed the tumor to be homogeneous and soft; intraoperatively, the tumor was 70% soft, but 30% was very firm in the region along the left internal carotid artery.* **B**, *a right-convexity meningioma that measured 6.5 cm in maximum diameter. Note the flow voids within the tumor, and preoperative angiography confirmed a highly vascular tumor. MRE showed the tumor to be soft and homogeneous. At surgery, the tumor was consistent throughout but required cautery to remove because it was fibrous.*

BACKGROUND: Magnetic resonance elastography (MRE) analyzes shear wave movement through tissue to determine stiffness. In a prior study, measurements with first-generation brain MRE techniques correlated with intraoperative observations of overall meningioma stiffness.

OBJECTIVE: To evaluate the diagnostic accuracy of a higher-resolution MRE technique to preoperatively detect intratumoral variations compared with surgeon assessment.

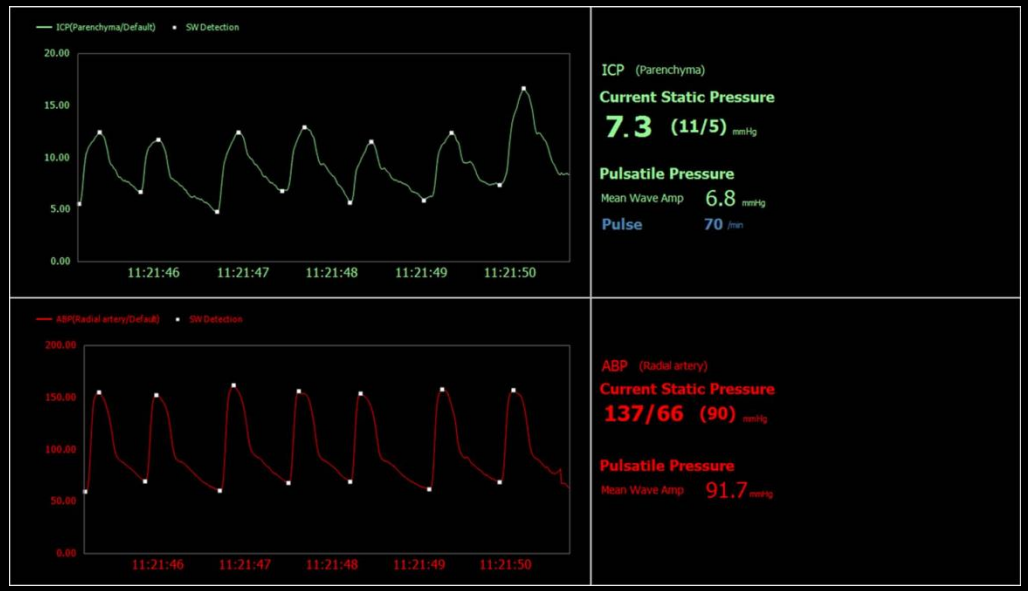
METHODS: Fifteen meningiomas in 14 patients underwent MRE. Tumors with regions of distinctly different stiffness were considered heterogeneous. Intratumoral portions were considered hard if there was a significant area $\geq$6 kPa. A 5-point scale graded intraoperative consistency. A durometer semiquantitatively measured surgical specimen hardness. Statistics included χ^2, sensitivity, specificity, positive and negative predicative values, and Spearman rank correlation coefficient.

RESULTS: For MRE and surgery, 9 (60%) and 7 (47%) tumors were homogeneous, 6 (40%) and 8 (53%) tumors were heterogeneous, 6 (40%) and 10 (67%) tumors had hard portions, and 14 (93%) and 12 (80%) tumors had soft portions, respectively. MRE sensitivity, specificity, and positive and negative predictive values were as follows: for heterogeneity, 75%, 100%, 100%, and 87%; for hardness, 60%, 100%, 100%, and 56%; and for softness, 100%, 33%, 86%, and 100%. Overall, 10 tumors (67%) matched well with MRE and intraoperative consistency and correlated between intraoperative observations ($P = .02$) and durometer readings ($P = .03$). Tumor size $\leq$3.5 cm or vascular tumors were more likely to be inconsistent ($P < .05$).

CONCLUSION: MRE was excellent at ruling in heterogeneity with hard portions but less effective in ruling out heterogeneity and hard portions, particularly in tumors more vascular or $<$3.5 cm. MRE is the first technology capable of prospectively evaluating intratumoral stiffness and, with further refinement, will likely prove useful in preoperative planning.

Reiss-Zimmermann 2015

Wagshull 2011 – Pulsating brain



Abstract

The maintenance of adequate blood flow to the brain is critical for normal brain function; cerebral blood flow, its regulation and the effect of alteration in this flow with disease have been studied extensively and are very well understood. This flow is not steady, however; the systolic increase in blood pressure over the cardiac cycle causes regular variations in blood flow into and throughout the brain that are synchronous with the heart beat. Because the brain is contained within the fixed skull, these pulsations in flow and pressure are in turn transferred into brain tissue and all of the fluids contained therein including cerebrospinal fluid. While intracranial pulsatility has not been a primary focus of the clinical community, considerable data have accrued over the last sixty years and new applications are emerging to this day. Investigators have found it a useful marker in certain diseases, particularly in hydrocephalus and traumatic brain injury where large changes in intracranial pressure and in the biomechanical properties of the brain can lead to significant changes in pressure and flow pulsatility. In this work, we review the history of intracranial pulsatility beginning with its discovery and early characterization, consider the specific technologies such as transcranial Doppler and phase contrast MRI used to assess various aspects of brain pulsations, and examine the experimental and clinical studies which have used pulsatility to better understand brain function in health and with disease.

Zorgani 2015 – Physiological vibrations

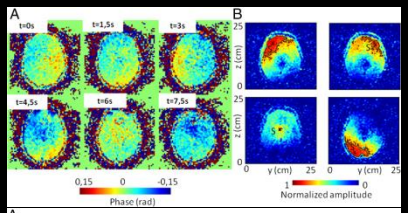


Fig. 3. In vivo brain results. (*A*) Phase representation of the displacement field. Six snapshots were extracted from a movie of 144 images. These in vivo measurements of brain motion were acquired with a gradient echo MRE sequence every 1.5 s. (*B*) Time-reversal focal spots in the brain for four different virtual source locations S. The isolevel black boundary lines stress the shear-wavelength variations.

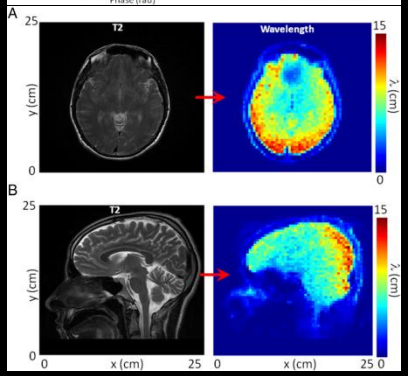


Fig. 4. In vivo brain passive MRE. (*A*) Axial view of (*Left*) the T2-weighted image and (*Right*) its corresponding shear-wavelength tomography. (*B*) Sagittal view of (*Left*) the T2-weighted image and (*Right*) its corresponding shear-wavelength tomography.

We present a magnetic resonance elastography approach for tissue characterization that is inspired by seismic noise correlation and time reversal. The idea consists of extracting the elasticity from the natural shear waves in living tissues that are caused by cardiac motion, blood pulsatility, and any muscle activity. In contrast to other magnetic resonance elastography techniques, this noise-based approach is, thus, passive and broadband and does not need any synchronization with sources. The experimental demonstration is conducted in a calibrated phantom and in vivo in the brain of two healthy volunteers. Potential applications of this "brain palpation" approach for characterizing brain anomalies and diseases are foreseen.