MR Elastography: Standardizing Terminology and Setting Guidelines

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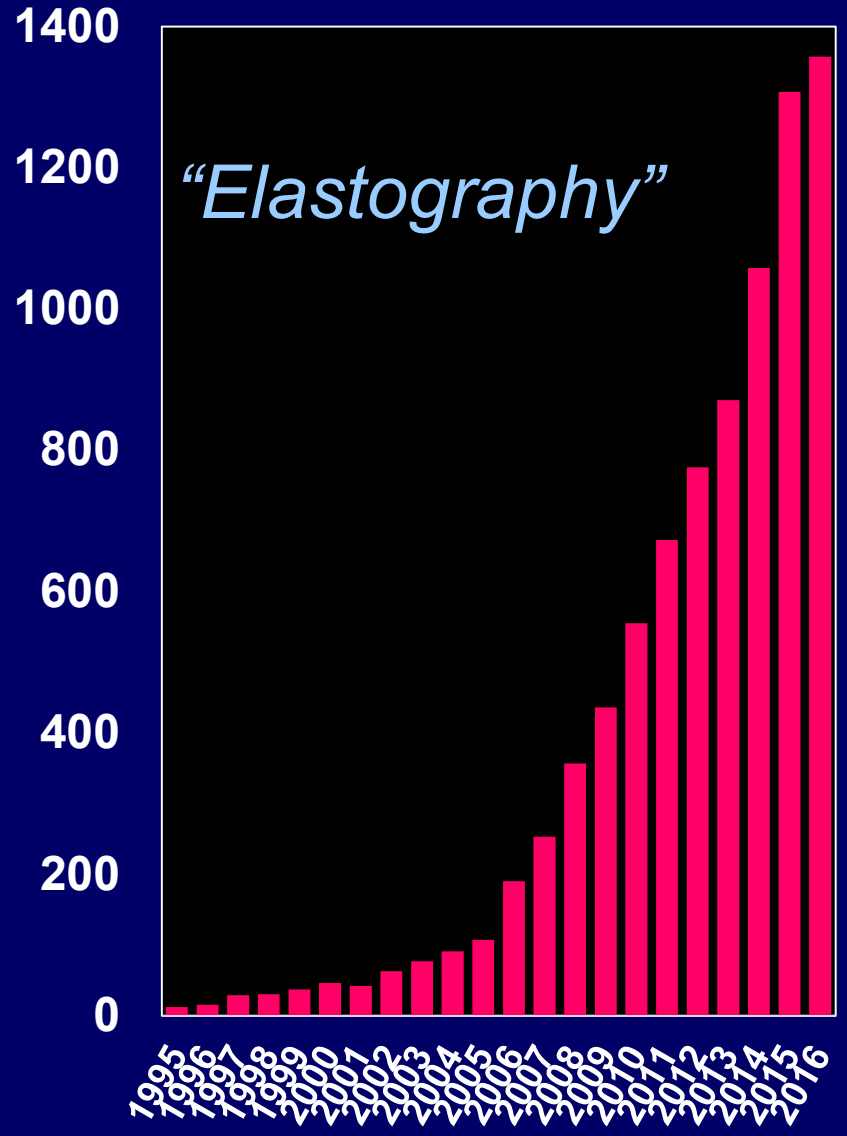
MR Elastography (MRE)

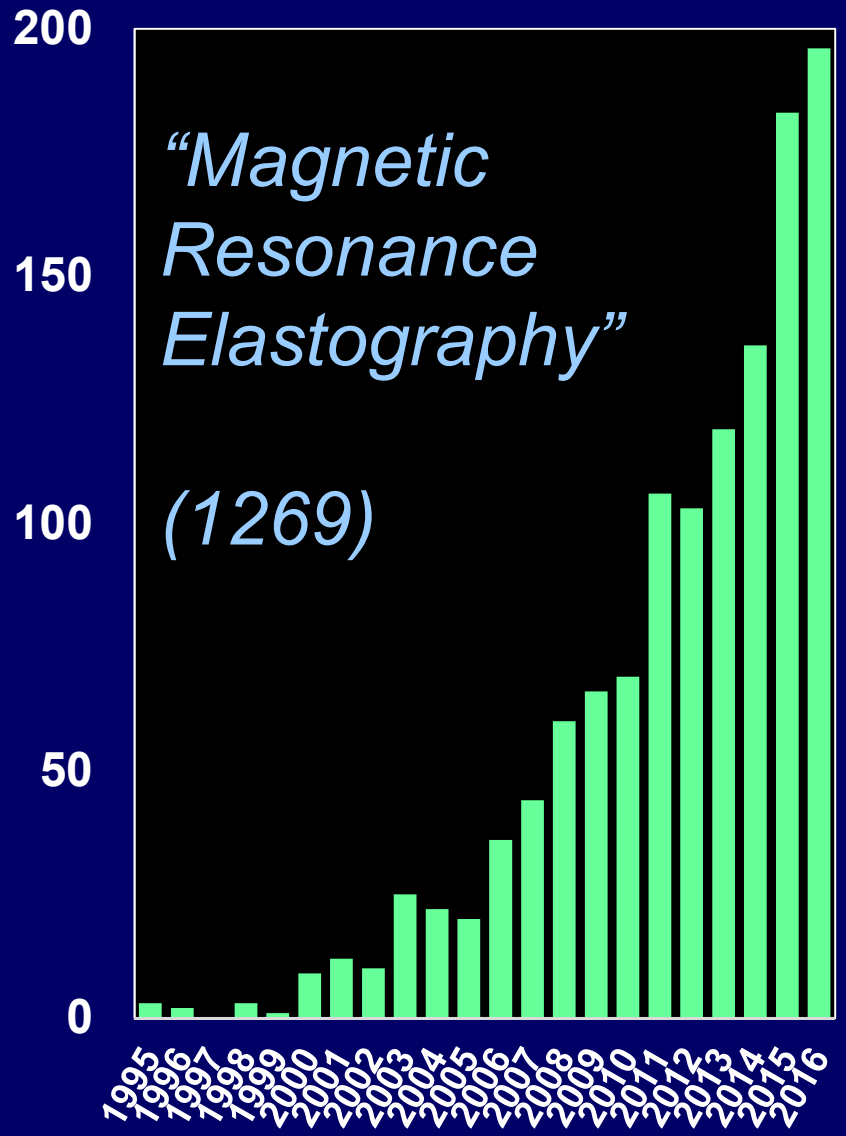
- Dynamic MRE is a phase-contrast MRI technique that can directly visualize and measure small harmonic mechanical displacements in tissue-like materials
- From this data, inversion algorithms can calculate mechanical properties such as shear modulus and attenuation
- This is *quantitative, non-invasive palpation*

MRE is Growing!

- MRE is increasing in clinical importance:
  - It has become widespread in the diagnosis and staging of liver fibrosis
  - May soon become useful in tumor surgery planning
  - Many other areas being researched.
- The research applications of MRE also continue to increase.
- The number of MRE papers per year is increasing rapidly.

Publications (*Web of Science*)





However..

- Many types of acquisitions and processing techniques are in use
- Many groups are reporting MRE results in terms of many different parameters
- There is some confusion (particularly among clinicians) as to the meaning of certain terms, or how to interpret certain types of MRE results
- Such issues could negatively impact the further growth of MRE

For example..

- MRE results have been reported as: shear modulus (sometimes complex), storage modulus, elasticity, magnitude of complex shear modulus, wave speed or wave speed squared, shear stiffness (defined in different ways), propagation…
- Loss-related parameters: loss modulus, attenuation, loss tangent, loss factor, phase angle, damping ratio, adjusted damping ratio, penetration rate…

For example..

- This is NOT an exhaustive list.
- The above are all at a single frequency! We haven't yet mentioned quantities related to specific material models (e.g. springpot parameters)
- Nor have we mentioned anisotropic or poroelastic parameters…

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- The above are all at a single frequency! We haven't yet mentioned quantities related to specific material models (e.g. springpot parameters)
- Nor have we mentioned anisotropic or poroelastic parameters…
- What are clinicians to make of this?
- Or researchers from a related field?

MRE Guidelines Committee

- The ISMRM MRE Study Group was proposed in late 2014 and first met at the 2015 annual meeting
- Soon after its founding, the initial leaders of the Study Group set up an MRE Guidelines Committee (the authors of this abstract)
- This committee has, among other things, set up a Study Group data repository, a Facebook page, and arranged for a physical MRE phantom to be passed among various MRE labs.

MRE Guidelines Committee

- One task identified by the Guidelines Committee was the drafting of a white paper, as a service to the MRE community, to tackle some of the above issues, and (to some extent) standardize MRE terminology and practice

Purpose of the White Paper

- Explain MRE terminology to those not familiar with it
- Recommend some practices and terms we believe should be standardized
- Try to define “good practices” for practitioners of MRE
- Recommend some practices and terms we believe should be discouraged or their use modified

Status of Paper

- A fairly detailed draft is circulating among the committee
- Most “recommendations” haven’t yet been voted on or are still being finalized
- Intent is to submit to MRM in the 3-6 month time scale
- Note: this is NOT a review paper

We Want Your Input!

- What would be important for such a paper to do or to consider?
- What recommendations should such a paper make?
- What do you personally think might confuse clinicians or outsiders that could be clarified?
- What do you feel strongly about?

Recommendations: Density

- Technically, density is an unknown parameter at each voxel, and most MRE inversions yield quantities such as G/ρ
- Except for the lung, most MRE groups (sometimes implicitly) assume tissue density of 1.00 g/cm^3 (or 1000 kg/m^3)
- Actual tissue densities vary, and are probably closer to 1.05 g/cm^3
- But: this can't be determined by MRE, is hard to assess independently, and literature values vary

Recommendations: Density

- Occasionally, a paper is written with such a more realistic value, or a reviewer asks why such a value was not used
- Cardiac MRI has standardized on 1.05 g/cm^3 for some types of analyses
- Strong consensus for: formally standardizing at 1.00 g/cm^3 (except for the lung, of course) – then comparisons between papers are easy, there's one less thing to worry about, and reviewer complaints can be addressed directly

Recommendations: Stiffness

- The word “stiffness” is used loosely by all of us, and makes intuitive sense to most people and to clinicians - but it’s technically incorrect
- Stiffness is defined as force/displacement, has units of N/m (not kPa), is a measure of rigidity of an *object*, and depends on its physical dimensions
- Shear modulus is an intrinsic material property; stiffness is a property of an object
- Notice that the concept of a map of stiffness variation inside an object doesn’t actually make sense

Recommendations: Stiffness

- But it's probably too late to change how we all use "stiffness", and clinicians have trouble understanding terms like "shear modulus"
- Possible answer: continue the use of "stiffness" for general comments, introductory or summary statements, comparisons, etc. – but when actually reporting results, use the correct term for the quantity reported – e.g. never say "stiffness is XXX kPa"

Reporting Results

- MRE results have been reported as: shear modulus (sometimes complex), storage modulus, elasticity, magnitude of complex shear modulus, wave speed or wave speed squared, shear stiffness (defined in different ways), propagation…
- Loss-related parameters: loss modulus, attenuation, loss tangent, loss factor, phase angle, damping ratio, adjusted damping ratio, penetration rate…

Reporting Results

- These are all convertible to one another – two independent quantities describe the behavior of shear waves in a viscoelastic, isotropic material
- Converting between these (e.g. to compare to previous results by other groups) is inconvenient, increases the possibility of error, slows down research (a little)…
- But different parameters may be more useful or correlate better with different effects
- How about: always express results as G' and G'', *in addition to* whatever other parameters are chosen?

Definitions, relations…

- **Definitions for all the terms above**
- **Relationships among these quantities, such as between G* = G' +iG" and waves propagating as**

$$\mathbf{u} = \hat{x}\, e^{-\alpha y} e^{i(\beta y - \omega t)}$$

$$c_s{}^2 = 2|G^*|^2/\rho(G' + |G^*|)$$

$$k = \omega\sqrt{(\rho/G^*)}$$

$$G' = \rho\omega^2 \frac{(\beta^2 - \alpha^2)}{(\beta^2 - \alpha^2)^2 + (2\alpha\beta)^2}$$

$$\alpha^2 = \rho\omega^2(|G|^* - G')/2|G^*|^2$$

$$\beta^2 = \rho\omega^2(G' + |G^*|)/2|G^*|^2$$

$$G'' = \rho\omega^2 \frac{2\alpha\beta}{(\beta^2 - \alpha^2)^2 + (2\alpha\beta)^2}$$

Reporting Results

- Results at different frequencies are not directly comparable, which is often not well understood by clinicians
- How about: when reporting results, always include the frequency – not just in the methods, but right there with the tables of results, and with the text discussing these
- When working at multiple frequencies, always also report result at each frequency (if possible)

Good Practices

- Always report all details of the experiment and processing – kernel sizes used in processing, details of all filters used, etc.
- Give some measure of maximum and/or typical tissue displacement amplitude if possible
- Assess reproducibility of technique/results if possible
- Assess and discuss sources of error (see next page)

Sources of Error

- Estimation errors even if there is a pure shear wave:
- Inversion algorithm is biased
- Noise corrupts and biases the results (to lower values)
- Noise effects are worse for stiffer objects/longer wavelengths
- Discretization biases the results (typically underestimates derivatives)
- Estimation errors due to longitudinal wave not being completely rejected (biases towards higher values)

Sources of Error

- Estimation errors due to anisotropic effects (shear waves have different speeds in different directions) or poroelastic effects (pressure term not accounted for)
- Estimation errors due to waveguide effects biasing algorithms that don't account for these
- Estimation errors due to heterogeneity effects biasing algorithms that don't account for these
- Problems when processing kernel extends across a boundary

Things We Need

- SNR measure that tells us when the data is “good enough”
- OSS-SNR is claimed to achieve this in a global sense for NLI
- But may not hold up as well in a regional sense, depends on processing parameters for other algorithms, and is fundamentally incorrect for direct-inversion type algorithms based on second derivatives
- Good measure for comparisons, such as between different drivers at same frequency for same object

Things We Need

- Quantitative confidence measures that actually assess coefficient of variation or give confidence intervals for results at a voxel
- Even this would only assess the effect of noise, not biases due to other effects mentioned above
- Automated measure of when phase unwrapping process has failed?

We Want Your Input!

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- Please contact me (manduca@mayo.edu) or any member of the committee with suggestions, questions, etc.

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