Rheolution Instruments

Viscoelastic Characterization of Biological Tissues & Biomaterials with Commercial Systems

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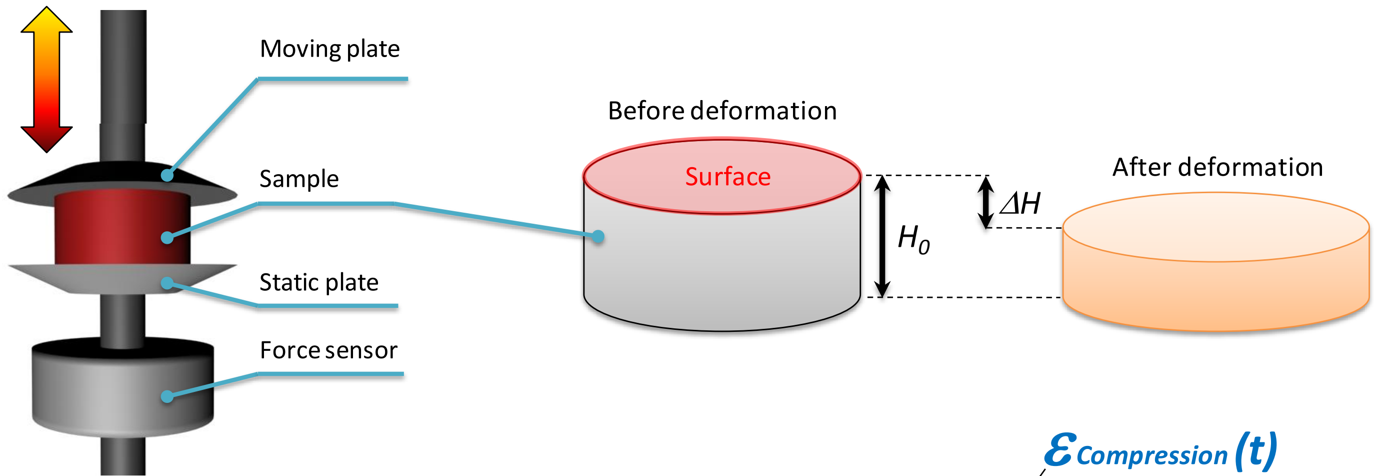
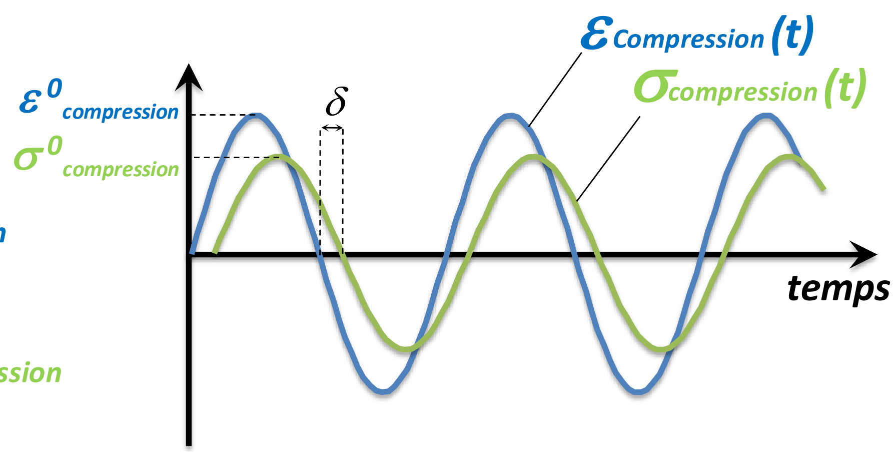
Objectives of this presentation

- To list and compare the different commercially available instruments for the viscoelastic characterization of materials and biomaterials,
- To give examples in the context of shear wave elastography calibration, in term of:
  - Large frequency range,
  - Small deformations,
  - Adaptation to soft biomaterials and soft biological tissues testing
    - Feasible tests
    - Samples preparation

Dynamic Mechanical Analysis (DMA) Systems : Principle





$$\frac{\Delta H}{H_0} = \text{deformation } \varepsilon_{compression}$$

$$\frac{\text{Measured Force}}{\text{Surface}} = \text{strain } \sigma_{compression}$$

Storage modulus

$$E' = \frac{\sigma_0}{\varepsilon_0} \cos(\delta)$$

Loss modulus

$$E'' = \frac{\sigma_0}{\varepsilon_0} \sin(\delta)$$

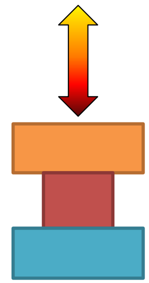
Deformation modes available in DMA systems

Moving part
Static part
Sample

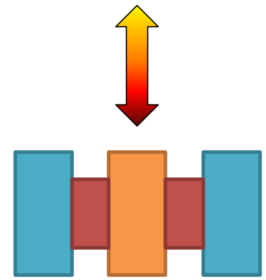
Medium Soft Samples (kPa to MPa)

⇧

depending on the sample

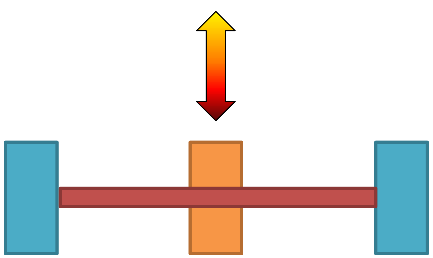


Compression (E', E'')

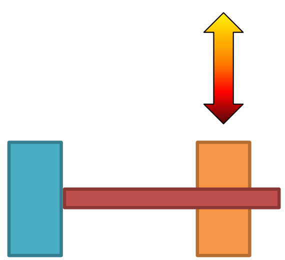


Shear (G', G'')

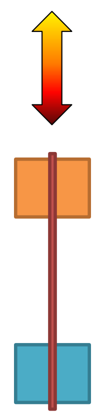
Rigid samples (MPa to GPa)



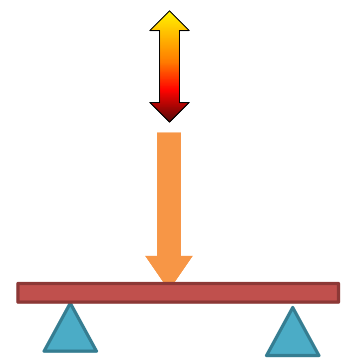
Dual cantilever (E', E'')



Single cantilever (E', E'')



Tension (E', E'')



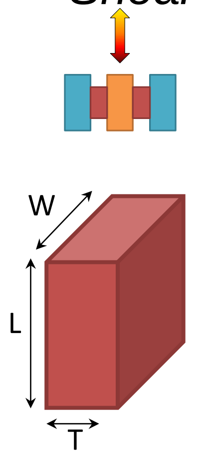
3-point bending (E', E'')

DMA: Deformation modes

DMA: Samples Dimensions

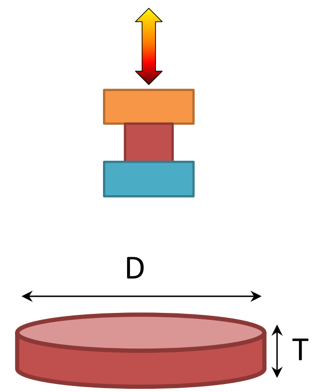
TA Instruments Q800

Shear



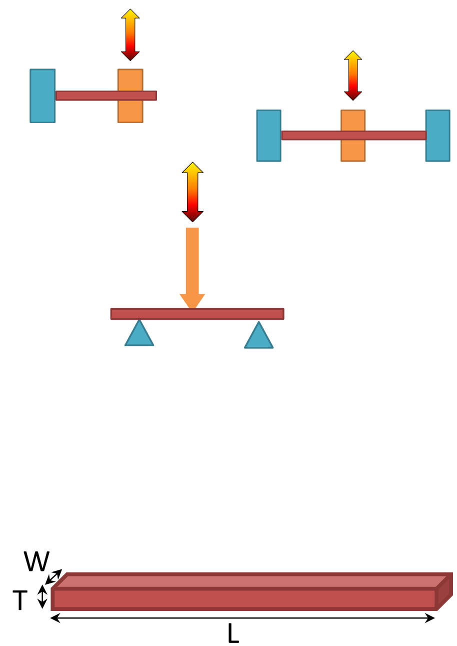
T = up to 4 mm
W = 10 mm
L = 10 mm

Compression



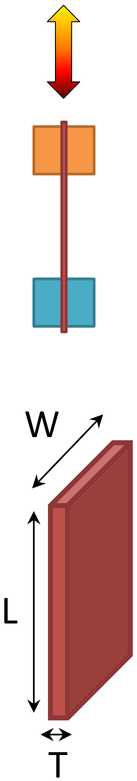
T = up to 10 mm
D = 15 mm or 40 mm

Bending



L = 4 mm to 50 mm
T = 5 mm
W = up to 15 mm

Tension

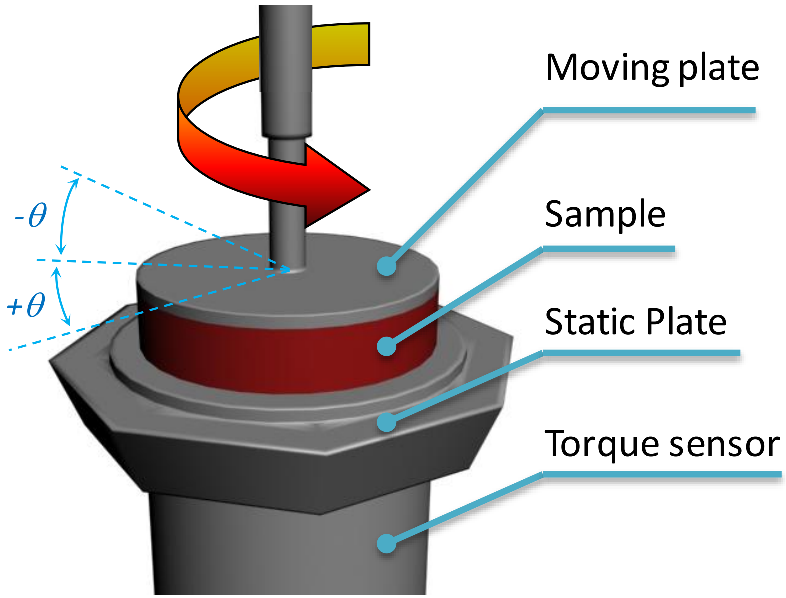


T = 2 mm
W = up to 8 mm
L = 5 to 30 mm

Limitations in the context of SWS calibration

- More adapted for rigid materials
- Not adapted for very small strain without pre-deformation
- One modality for G', G'' measurement
- **Cannot reach high frequencies due to system inertia**

Oscillatory Rheometry : Principle

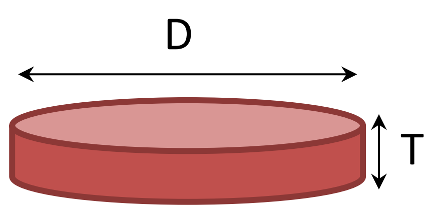


Basic relations:

$$G' = \frac{\sigma_0}{\varepsilon_0} cos(\delta) \qquad G'' = \frac{\sigma_0}{\varepsilon_0} sin(\delta)$$

- **Deformation modes : Rotational Shear**
- **Sample stiffness: Pa to kPa**

- **Sample Dimensions**



D = 20T to 28T

D = 20 mm	⇨	T = 0.71-1 mm
D = 30 mm		T = 1.07-1.5 mm
D = 50 mm		T = 1.73 -2.5 mm

Limitations in the context of SWS calibration

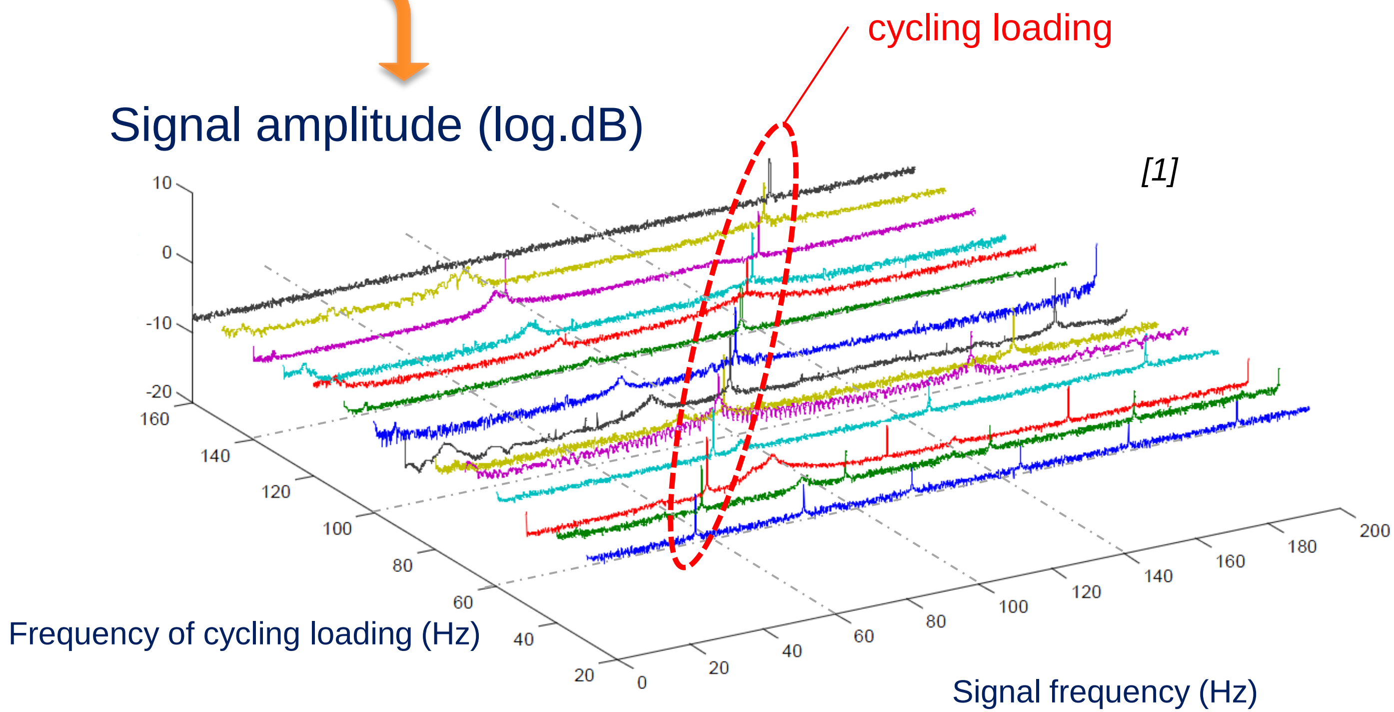
- ➢ More adapted for fluid testing
- ➢ Cannot test rigid samples
- ➢ Very sensitive to the sample geometry (surface flatness, thickness) and pre-stress
- ➢ Cannot reach high frequencies due to system inertia

Origin of the frequency range limitation for the DMA and rheometer instruments

- Sample-holder resonance
- Sample resonance
- Instrument resonance

Laser vibrometer [1]

ElectroForce 3200 (Bose)



[1] *Placet, V.; Foltête, E.,* Is Dynamic Mechanical Analysis (DMA) a non-resonance technique?, *ICEM 14 – 14th International Conference on Experimental Mechanics, Poitiers, France, EPJ Web of Conferences, Volume 6, id.41004, 2010.*

Time-Temperature Superposition (TTS) principle

- **Indirect measurements**

Hypothesis:

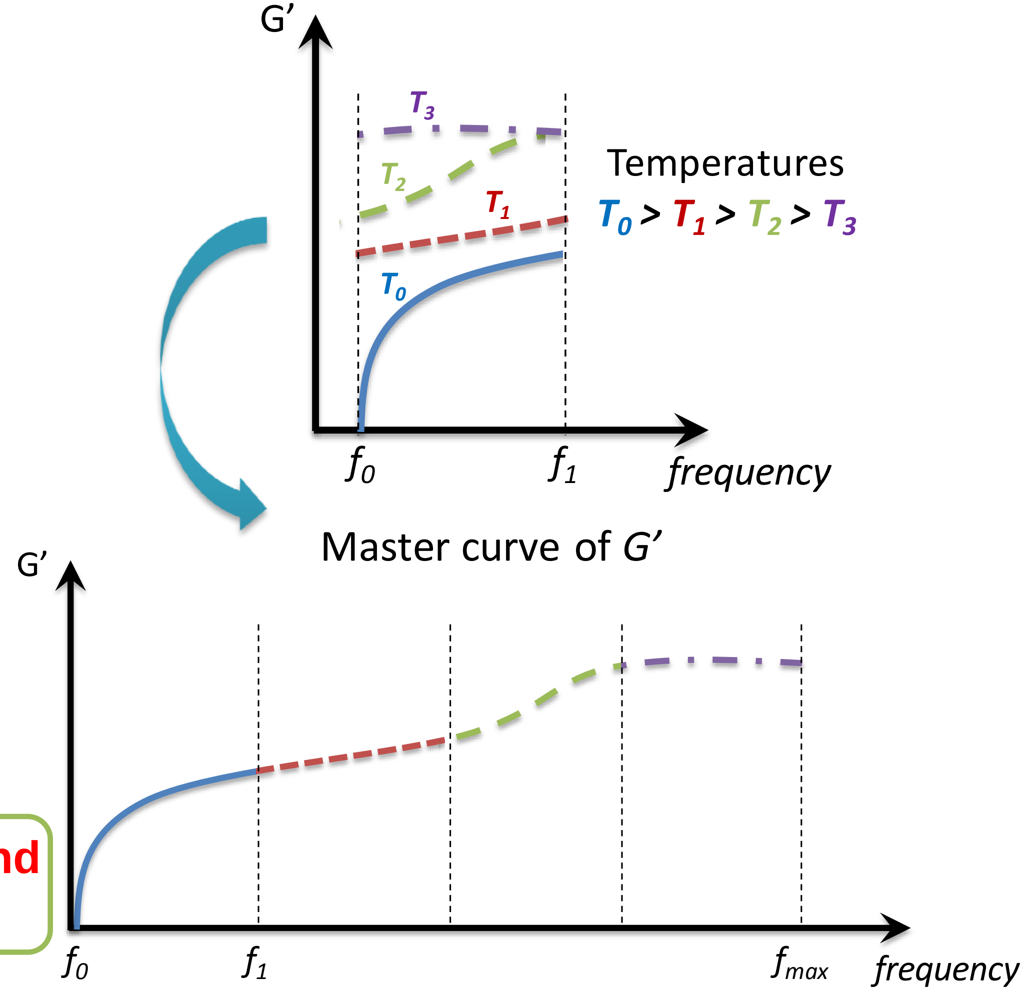
•"Thermorheologically" simple materials

⇓

The material presents a similar behavior for different temperatures

⇓

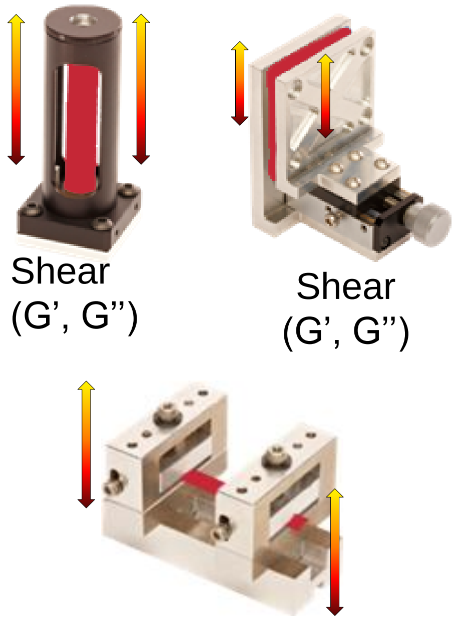
Assumption not valid for biomaterials and biological tissues[23-27]



[23] M. van Turnhout et al., Passive transverse mechanical properties as a function of temperature of rat skeletal muscle in vitro, *Biorheology*, vol. 42, no. 3, pp. 193-207, 2005.
[24] N.T. Wright et al., Denaturation of collagen via heating: an irreversible rate process, *Annu.Rev.Biomed.Eng*, vol. 4, pp. 109-128, 2002.
[25] E. Tornberg, Effects of heat on meat proteins - Implications on structure and quality of meat products, *Meat Science*, vol. 70, no. 3, pp. 493-508, 2005.
[26] M.Z. Kiss et al., Investigation of temperature-dependent viscoelastic properties of thermal lesions in ex vivo animal liver tissue, *J.Biomech.*, vol. 42, no. 8, pp. 959-966, 2009.
[27] E. Sapin-de Brosses et al., Temperature dependence of the shear modulus of soft tissues assessed by ultrasound, *Phys.Med.Biol.*, vol. 55, no. 6, pp. 1701-1718, 2010.

Hyper-Frequency Viscoelastic Spectroscope (HFVS) : Principle

Samples & Holders subjected to vibration

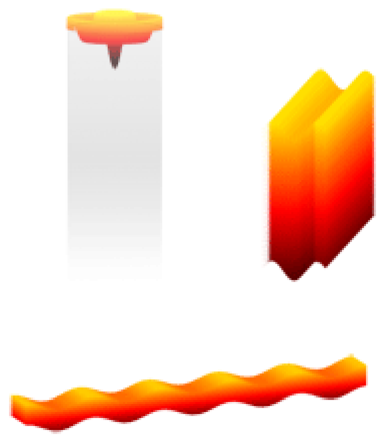


Shear
(G', G")

Shear
(G', G")

Single/dual cantilever
(E', E")

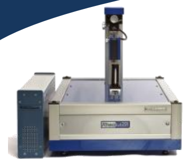
Measurement of the Sample Vibration



Data Processing over a large frequency range

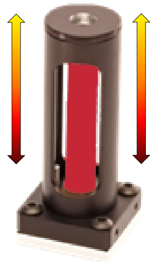
G', G", tan δ
or
E', E", tan δ

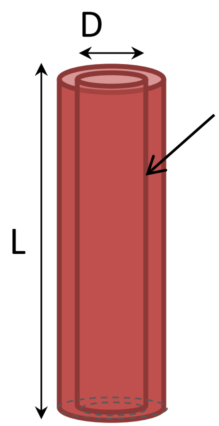
HFVS: Samples Dimensions



RheoSpectris C400 (Rheolution)

Cylinder



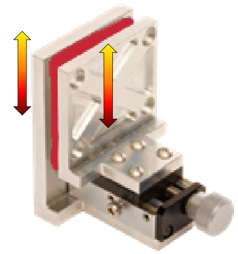


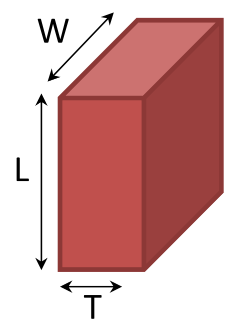
Cylindrical container for pourable material

D = 9.5 mm

L = 76 mm

Slice



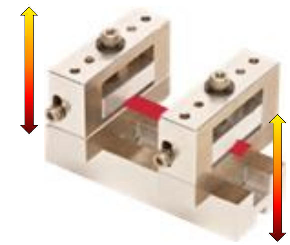


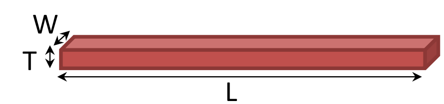
T = 3 to 12 mm

$W \geq 4T$

$L \geq 4T$

Beam / Fiber

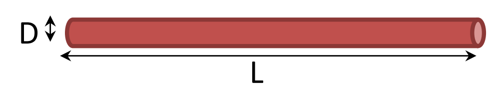




L = 6 mm to 66 mm

$T \leq L/17$

$W \approx T$

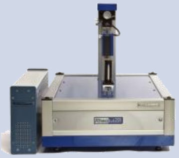


L = 6 mm to 66 mm

$D \leq L/17$

HFVS: Samples dimensions

Commercial Instruments

DMA systems	Frequency range	Stiffness range	Rheometer systems	Frequency range	Stiffness range	HFVS	Frequency range	Stiffness range
 ElectroForce 3200 (Bose)	10 µHz to 150 Hz	Compression (E', E'') 100 Pa* to GPa	 Physica MCR (Anton Paar)	0.0159 µHz to 100 Hz	Shear (G', G'') mPa to kPa*	 RheoSpectris C400 (Rheolution)	10 Hz to 2000 Hz	Shear (G', G'') 10Pa to 1 MPa Bending (E', E'') 1MPa to 500 GPa
 Q800 (TA Instruments)	0.01 Hz to 200 Hz	1kPa* to GPa	 ARES-G2 (TA Instruments)	0.0159 µHz to 100 Hz	Shear (G', G'') mPa to kPa*			
 ELECTROPULS (Instron)	Up to 100 Hz	kPa* to GPa	 HAAKE MARS (Thermo Scientific)	1 µHz to 150 Hz	Shear (G', G'') mPa to kPa*			
 DMA/SDTA861e (Mettler Toledo)	*Shear mode:* 0.01 Hz to 1000 Hz *Bending/tension/compression* 0.01 Hz to 300 Hz	Shear mode (G', G'') 1 kPa* to 1GPa Tension/compression (E', E'') 0.1 MPa* to 30 GPa Bending (E', E'') Up to 500 GPa	 Kinexus (Malvern)	10 µHz to 100 Hz	Shear (G', G'') mPa to kPa*			

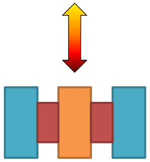
* Depending on the sample, the strain rate and the frequency range.

Rheolution inc.: www.rheolution.com
Bose : http://worldwide.bose.com
TA instruments: http://www.tainstruments.com
Instron : www.instron.com
Mettler Toldeo: ca.mt.com
Anton Paar: www.anton-paar.com
Thermo Scientific: www.thermoscientific.com
Malvern: www.malvern.com

Applications in the literature : Elastography

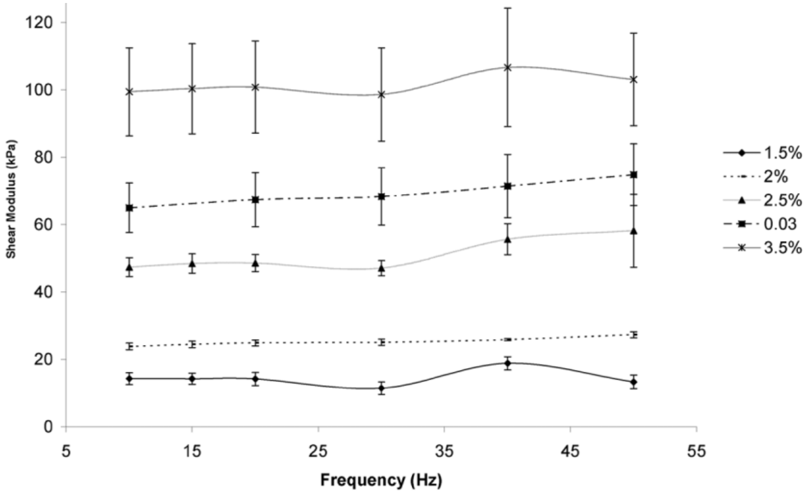
DMA
(Q800, TA Instruments)

Shear

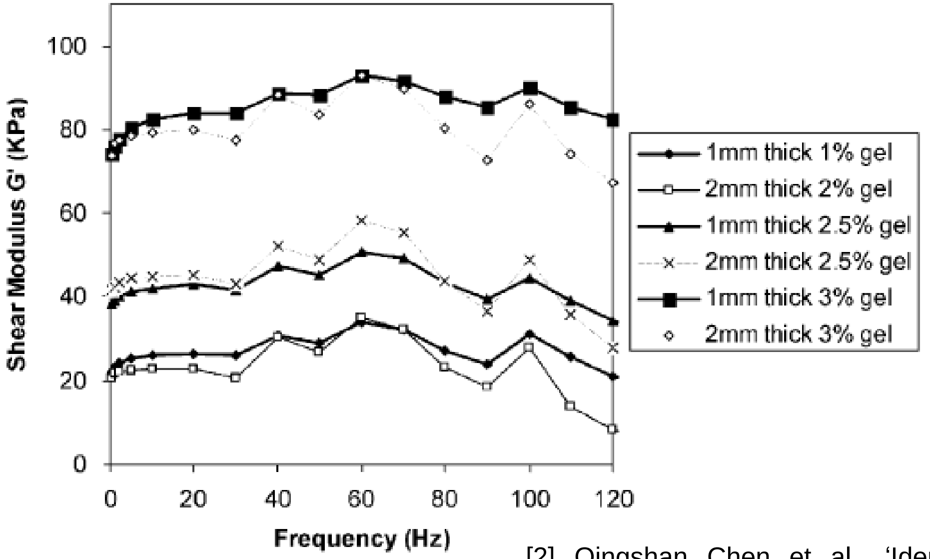


Validation of MRI elastography on agar samples by using a DMA instrument[2][3]

Agarose gel with concentrations ranging from 1.5 to 3.5% in 0.5% (sample dimension: 5.5 mm × 10 mm × 1-2 mm)[3]



Gels with agar concentration of 2%, 2.5% and 3% (sample dimension: 5.5 mm × 10 mm × 1-2 mm)[2]



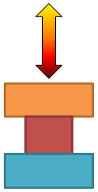
[2] Qingshan Chen et al., ‘Identification of the testing parameters in high frequency dynamic shear measurement on agarose gels’, Journal of Biomechanics 38, 959–963, 2005.
[3] Stacie I. Ringleb et al., Quantitative Shear Wave Magnetic Resonance Elastography: Comparison to a Dynamic Shear Material Test, Magnetic Resonance in Medicine 53:1197–1201, 2005.

Applications in the literature : Elastography

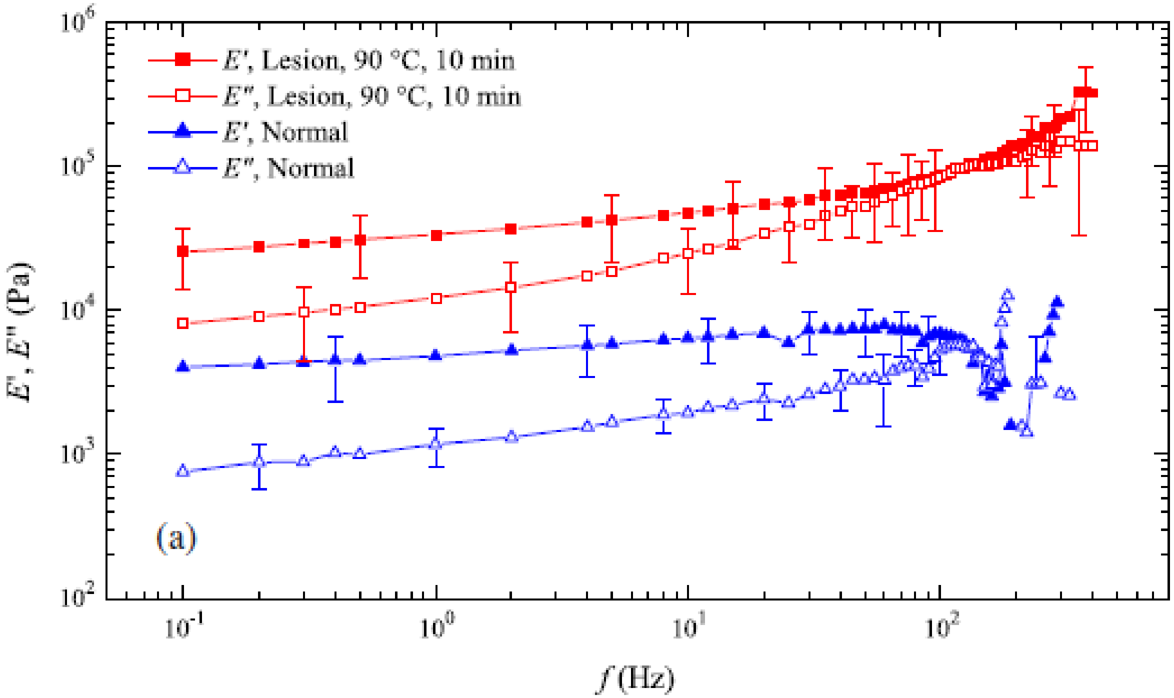
DMA
(ElectroForce 3200, Bose)

In vitro viscoelastic characterization of canine liver using a DMA instrument[4]

Compression



Canine liver (fresh or after thermal ablation)
(sample dimension: 20 mm in diameter, thickness around 5 mm)[1]

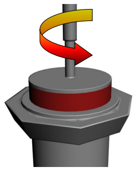


[4] Miklos Z Kiss et al., Viscoelastic characterization of in vitro canine tissue, Phys. Med. Biol. 49, 4207–4218, 2004.

Applications in the literature : Elastography

Rheometer
(Physica MCR, Anton Paar)

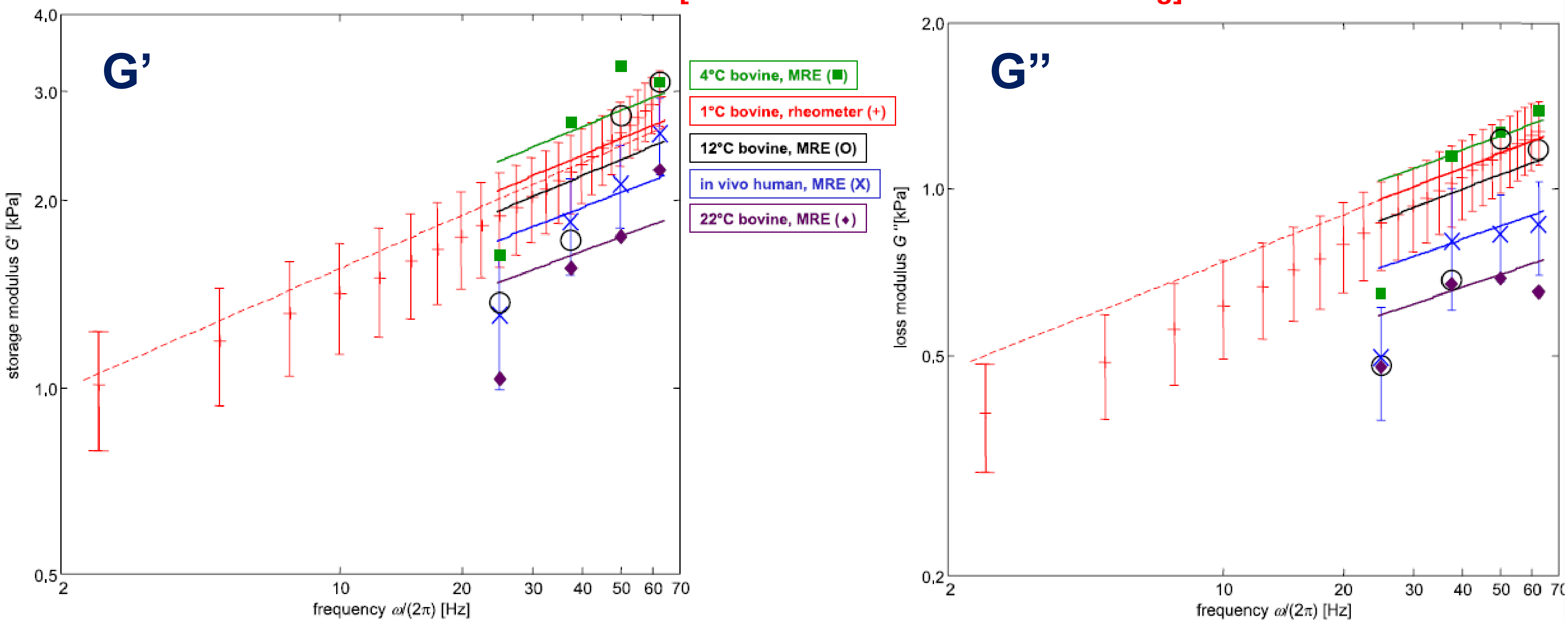
Rotational shear



Validation of MRI elastography on bovine liver using a rotational rheometer instrument[5]

Bovine liver (sample dimensions: 50 mm diameter and a slice thickness of 0.9–2.4 mm)

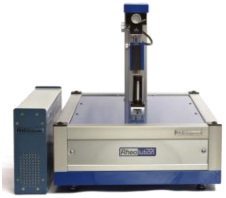
[Liver tested at 1°C to avoid clotting]



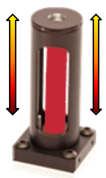
[5] Dieter Klatt, Viscoelastic properties of liver measured by oscillatory rheometry and multifrequency magnetic resonance elastography, Biorheology 47, 133–141, 2010.

Applications in the literature : Elastography

HFVS
(RheoSpectris C400, Rheolution)



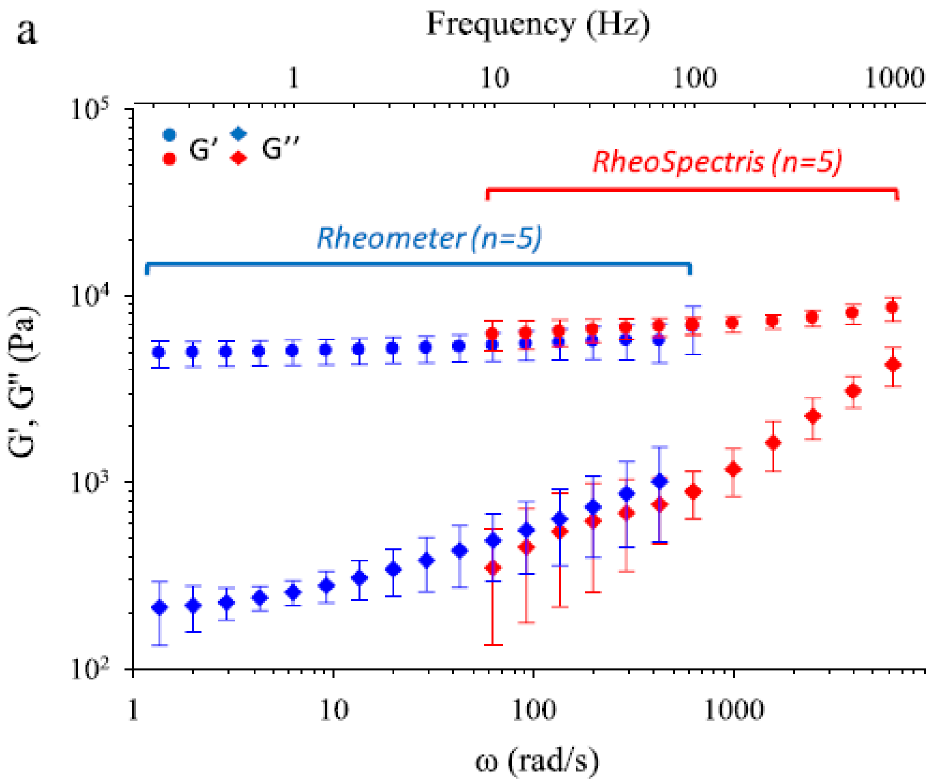
shear



Hyper-frequency viscoelastic spectroscopy of biomaterials and elastography phantoms [6]

Polyvinyl alcohol cryogel (PVA-C)

(samples dimensions: 9-14 mm diameter, 70-80 mm long)



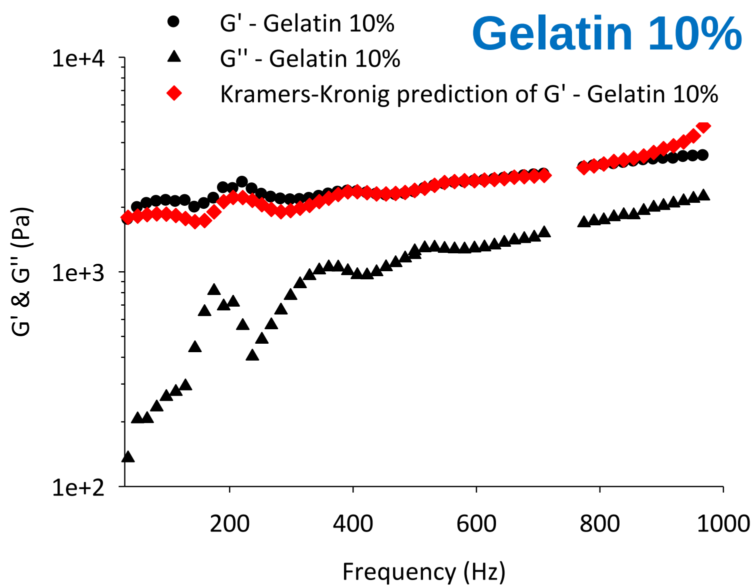
(Small strain :1.8%)

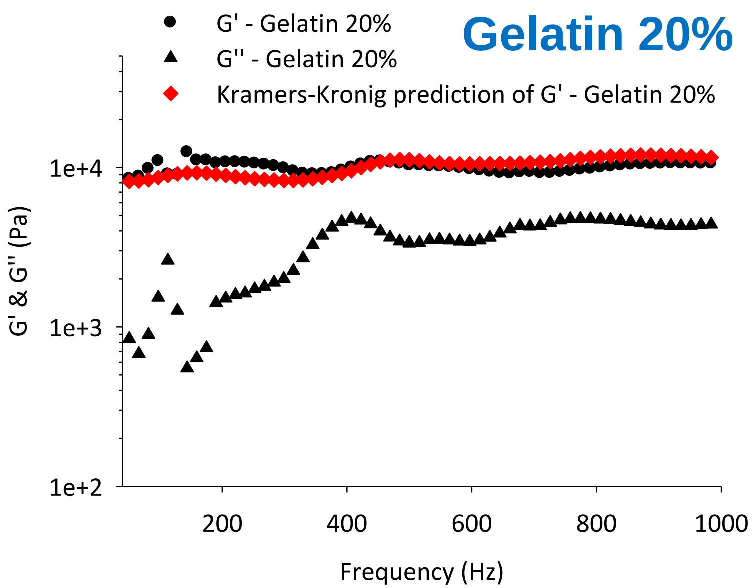
[6] A. Hadj Henni et al., Hyper-frequency viscoelastic spectroscopy of biomaterials, J. Mech. Behav. Biomed. Mater., 4(7):1115-22, 2011.

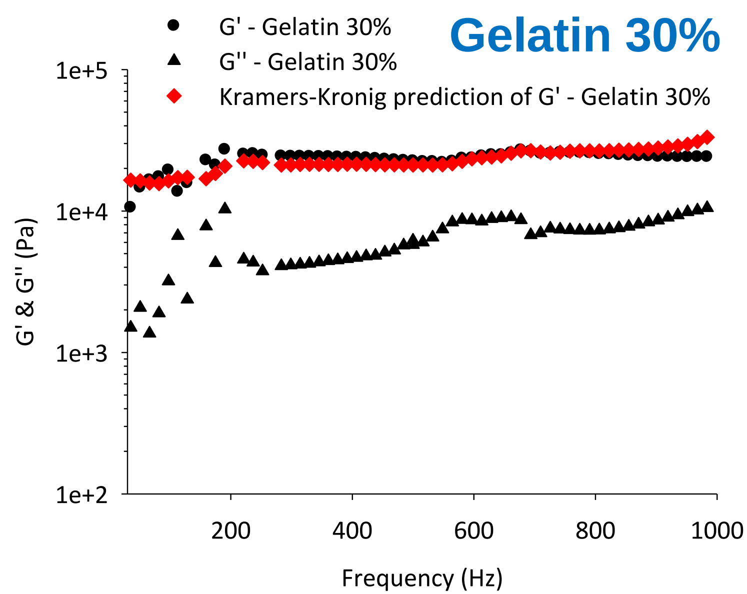
Example HFVS of gelatin using RheoSpectris C500

- Measurement of complex shear modulus of commercial gelatin at three different concentrations: 10%, 20% and 30%.

- Conformity of measurements to the causality principle (Kramers-Kronig)[21,22]:
  - Kramers–Kronig: bidirectional mathematical relations connecting the real and imaginary parts of G' and G'',
  - Verify the causality: measurements where the output depends on past and current measurements but not future inputs.





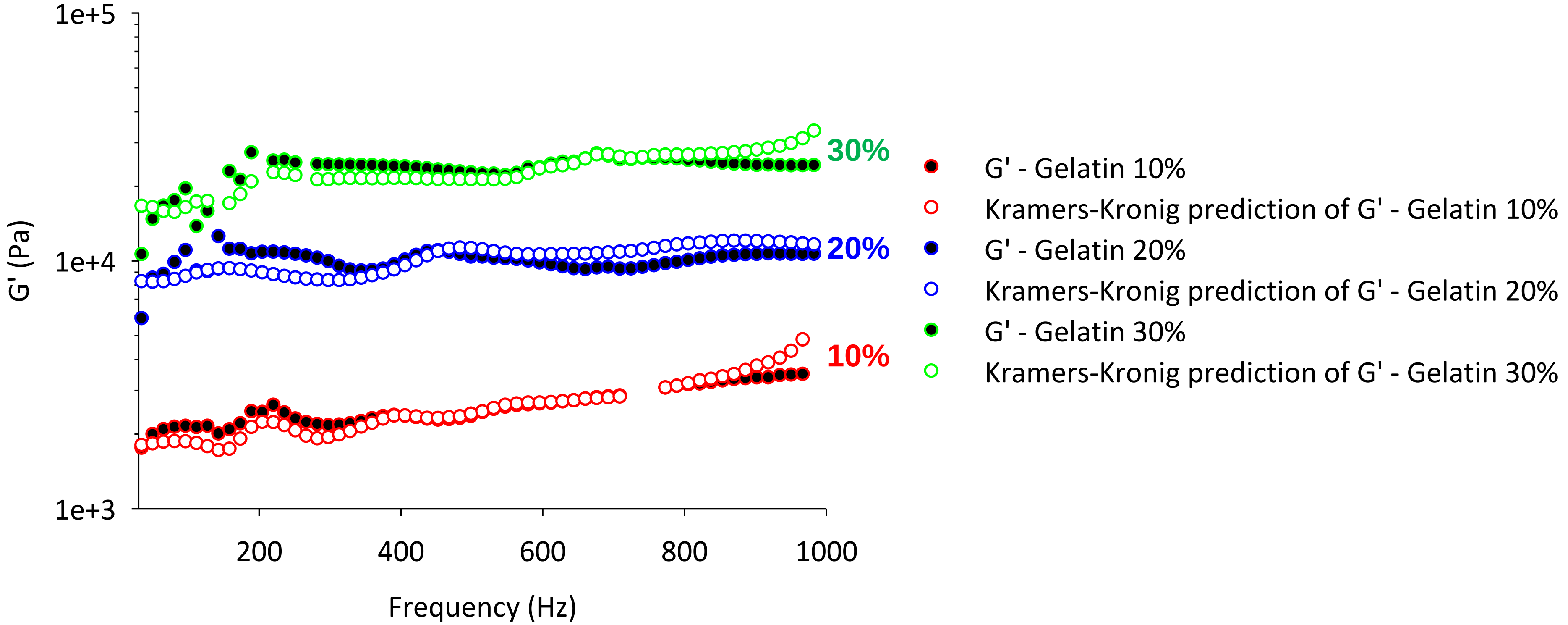


[21] Rod Lakes, Viscoelastic Materials, Cambridge University Press, (2009).
[22] Ferry, J.D., 1980. Viscoelastic Properties of Polymers. John Wiley & Sons, New York.

Conformity of measurements to the causality principle[21,22]

$$G'(\omega) - G'(\infty) = \frac{2}{\pi} P \int_0^{\infty} \frac{\beta\, G''(\beta)}{\beta^2 - \omega^2} d\beta$$

Comparison of the measured storage moduli (G') with the calculated storage moduli predicted from the measured loss moduli (G'') using the Kramers-Kronig relation



[21] Rod Lakes, Viscoelastic Materials, Cambridge University Press, (2009).
[22] Ferry, J.D., 1980. Viscoelastic Properties of Polymers. John Wiley & Sons, New York.

Rheolution

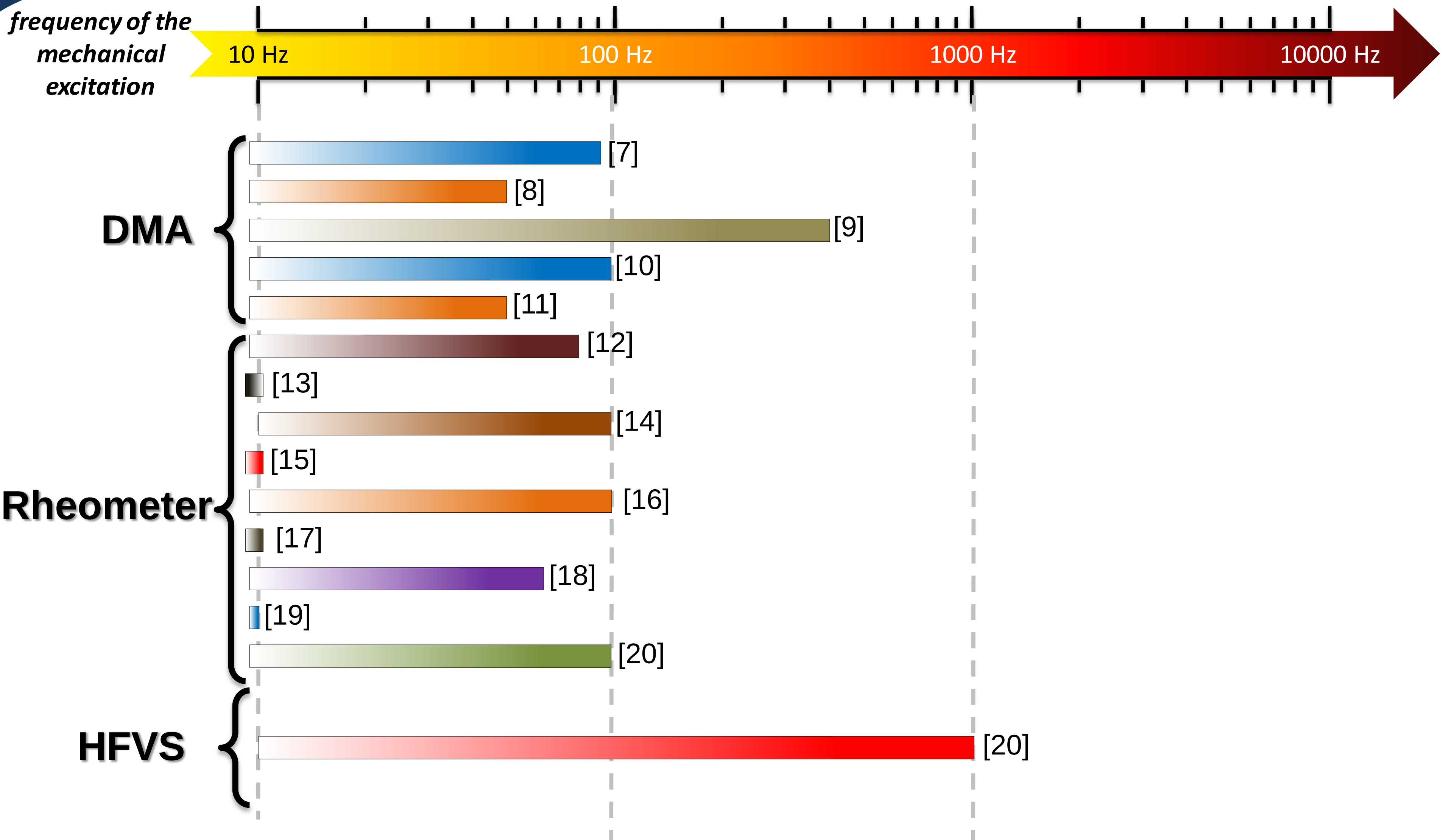
Ref	Instrument	Mode	Sample	Sample dimensions	Frequency range	Stiffness range
[7]	DMA (TA Instruments)	shear	agar	5.5 * 10 * 1-2 mm^3	0.1 to 90 Hz	G' = 10kPa-95kPa
[8]	DMA (Electroforce)	compression	Porcine and canine liver	20 mm diameter, 3-5 mm thick	0.1 to 50 Hz	|E*| = 13kPa-45kPa
[9]	DMA (Electroforce)	compression	Canine liver (fresh and after thermal treatment)	20 mm in diameter, ~ 5 mm thick	0.1 to 400 Hz	|E*| = 4kPa-400kPa
[10]	DMA (Electroforce)	compression	human uterine tissue	Rectangular : 10–20 mm	0.1 to 100 Hz	|E*| = 35kPa-95kPa
[11]	DMA (TA Instruments)	shear	agar	5.5 * 10 * 2 mm^3	10 to 50 Hz	G' = 15kPa-100kPa
[12]	Rheometer (TA instruments)	rotational shear	gelatin	40mm diameter, 1mm thick	1 to 80 Hz	G' = 1.3kPa to 1.4kPa
[13]	Rheometer (TA instruments)	rotational shear	Copolymer-in-oil	20 mm in diameter 3 mm thick	0.01 Hz to 3 Hz	G' ~ 1 kPa
[14]	Rheometer (Anton Paar)	rotational shear	agar	60 mm diameter 2 mm thick	10 Hz to 100 Hz	G' = 4kPa to 30kPa
[15]	Rheometer (TA instruments)	rotational shear	polyacrylamide gel, Agar-gelatin	10 mm diameter 4 mm thick	0.1 Hz to 10 Hz	G' = 1kPa to 3.5kPa

Overview

Ref	Instrument	Mode	Sample	Sample dimensions	Frequency range	Stiffness range
[16]	Rheometer (Anton Paar)	rotational shear	Polyacrylamide	50 mm diameter 1-2 mm thick	0.5 Hz to 100 Hz	G’ = 10 Pa to 20kPa
[17]	Rheometer (TA instruments)	rotational shear	Porcine brain	20 mm diameter 4-5 mm thick	0.1 Hz to 10 Hz	G’ = 400 Pa to 1.4kPa
[18]	Rheometer (Anton Paar)	rotational shear	Bovine liver	50 mm diameter 0.9-2.4 mm thick	2.5 Hz to 62.5 Hz	G’ = 1 kPa to 3kPa
[19]	Rheometer (TA instruments)	rotational shear	Porcine liver	20 mm diameter 3-5 mm thick	0.1 Hz to 4 Hz	G’ = 320Pa to 600Pa
[20]	Rheometer (Anton Paar)	rotational shear	Silicone Polyvinyl chloride PVA-C Chitosan hydrogel Agar–gelatin gel	25 mm diameter 0.1-1.5 mm thick	0.01 Hz to 100 Hz	G’ = 2 kPa to 30 kPa
[20]	HFVS (Rheolution inc)	shear	Silicone Polyvinyl chloride PVA-C Chitosan hydrogel Agar–gelatin gel	9-14 mm diameter 70-80 mm long	10 Hz to 1000 Hz	G’ = 200 Pa to 45kPa

Overview

Rheolution



Overview

References

[1] Placet, V.; Foltête, E., Is Dynamic Mechanical Analysis (DMA) a non-resonance technique?, ICEM 14 – 14th International Conference on Experimental Mechanics, Poitiers, France, EPJ Web of Conferences, Volume 6, id.41004, 2010.

[2] Qingshan Chen et al., 'Identification of the testing parameters in high frequency dynamic shear measurement on agarose gels', Journal of Biomechanics 38 (2005) 959–963.

[3] Stacie I. Ringleb et al., Quantitative Shear Wave Magnetic Resonance Elastography: Comparison to a Dynamic Shear Material Test, Magnetic Resonance in Medicine 53:1197–1201 (2005).

[4] Miklos Z Kiss et al., Viscoelastic characterization of in vitro canine tissue, Phys. Med. Biol. 49, 4207–4218, 2004.

[5] Dieter Klatt, Viscoelastic properties of liver measured by oscillatory rheometry and multifrequency magnetic resonance elastography, Biorheology 47, 133–141, 2010.

[6] A. Hadj Henni et al., Hyper-frequency viscoelastic spectroscopy of biomaterials, J. Mech. Behav. Biomed. Mater., 4(7):1115-22, 2011.

[7] Qingshan Chen et al., Identification of the testing parameters in high frequency dynamic shear measurement on agarose gels, Journal of Biomechanics 38, 959–963, 2005.

[8] Miklos Z.Kiss et al., Investigation of temperature-dependent viscoelastic properties of thermal lesions in ex vivo animal liver tissue, Journal of Biomechanics 42, 959–966, 2009.

[9] Miklos Z Kiss et al., Viscoelastic characterization of in vitro canine tissue, Phys. Med. Biol. 49, 4207–4218., 2004

[10] Miklos Z Kiss, Frequency-dependent complex modulus of the uterus: preliminary results, Phys. Med. Biol. 51, 3683–3695, 2006.

[11] Stacie I. Ringleb et al., Quantitative Shear Wave Magnetic Resonance Elastography: Comparison to a Dynamic Shear Material Test, Magnetic Resonance in Medicine 53:1197–1201, 2005.

[12] P.V. Bayly et al., Magnetic resonance measurement of transient shear wave propagation in a viscoelastic gel cylinde, Journal of the Mechanics and Physics of Solids 56, 2008.

[13] J. Oudry et al., Copolymer-in-oil phantom materials for elastography. Ultrasound in Med. & Biol., Vol. 35, No. 7, pp. 1185–1197, 2009.

[14] Sebastian Papazoglou et al., Multifrequency inversion in magnetic resonance Elastography, Phys. Med. Biol. 57, 2329–2346, 2012.

[15] Jonathan Vappou et al., Quantitative viscoelastic parameters measured by harmonic motion imaging, Phys. Med. Biol. 54, 3579–3594, 2009.

[16] Kishore Kumar et al., Measurement of Viscoelastic Properties of Polyacrylamide-Based Tissue-Mimicking Phantoms for Ultrasound Elastography Applications, IEEE Transactions on instrumentation abd measurement, Vol.59, No 5, 2010.

[17] Jonathan Vappou et al., Magnetic resonance elastography compared with rotational rheometry for in vitro brain tissue viscoelasticity measurement, Magn Reson Mater Phy, 2007.

[18] Dieter Klatt, Viscoelastic properties of liver measured by oscillatory rheometry and multifrequency magnetic resonance elastography, Biorheology 47, 133–141, 2010.

[19] Simon Chatelin, In vivo liver tissue mechanical properties by transient elastography: Comparison with dynamic mechanical analysis, Biorheology 48, 75–88, 2011.

[20] A. Hadj Henni et al., Hyper-frequency viscoelastic spectroscopy of biomaterials, J. Mech. Behav. Biomed. Mater., 4(7):1115-22, 2011.

[21] Rod Lakes, Viscoelastic Materials, Cambridge University Press, (2009).

[22] Ferry, J.D., 1980. Viscoelastic Properties of Polymers. John Wiley & Sons, New York.

[23] M. van Turnhout et al., Passive transverse mechanical properties as a function of temperature of rat skeletal muscle in vitro, Biorheology, vol. 42, no. 3, pp. 193-207, 2005.

[24] N.T. Wright et al., Denaturation of collagen via heating: an irreversible rate process, Annu.Rev.Biomed.Eng, vol. 4, pp. 109-128, 2002.

[25] E. Tornberg, Effects of heat on meat proteins - Implications on structure and quality of meat products, Meat Science, vol. 70, no. 3, pp. 493-508, 2005.

[26] M.Z. Kiss et al., Investigation of temperature-dependent viscoelastic properties of thermal lesions in ex vivo animal liver tissue, J.Biomech., vol. 42, no. 8, pp. 959-966, 2009.

[27] E. Sapin-de Brosses et al., Temperature dependence of the shear modulus of soft tissues assessed by ultrasound, Phys.Med.Biol., vol. 55, no. 6, pp. 1701-1718, 2010.