**Specialty area:**
Quantitative Musculoskeletal Imaging: Structure & Function - Muscle Structure & Functional Imaging

**Speaker name:**
Professor Neil Roberts,
Clinical Research Imaging Centre (CRIC),
School of Clinical Sciences,
The Queen's Medical Research Institute (QMRI),
College of Medicine and Veterinary Medicine (CMVM),
University of Edinburgh

e-mail: neil.roberts@ed.ac.uk

**Highlights**

- Magnetic Resonance Elastography (MRE) is providing new insights regarding muscle structure and function
- High resolution structural imaging of resting muscle visco-elastic properties
- Functional MRE-based statistical parametric mapping of muscle contraction
- Do muscles become more or less stiff with age?
- Super resolution and other developments in MRE image analysis
- What is the ideal human-machine interface and protocol for muscle MRE?

**TALK TITLE:**
Muscle Structure Including Magnetic Resonance Elastography (MRE)

**TARGET AUDIENCE:**
Physicists wishing to establish data acquisition and analysis protocols for performing MRE, image analysts interested in pioneering the development of new techniques to measure muscle structure and function, clinicians and life scientists interested in studying muscle anatomy, performance and physiology in health and disease.

**OUTCOME/OBJECTIVES:**
The aim of the research programme in this laboratory is to develop MRE data acquisition and analysis protocols so that the MRE technique provides robust, fully quantitative, high resolution images of tissue visco-elastic properties.

**PURPOSE:**
The above developments will enable MRE to be used both in routine Radiological diagnosis and for detailed statistical parametric mapping of changes in muscle structure, function and physiology over time and between cohorts.

**METHODS:**
MRE is a phase contrast imaging technique that measures the propagation of acoustic waves, introduced in a tissue of interest by means of a so-called actuator, using synchronised magnetic field gradients (Muthupillai et al., 1995). MRE was developed at the MAYO Clinic, where researchers have a longstanding interest in the application of MRE to detect and quantify liver fibrosis. The MAYO MRE research group also

pioneered the application of MRE to identify regions of abnormal muscle stiffness and to study changes in muscle stiffness following contraction (Chen et al., 2007; Bensamoun et al., 2008). A review of MRE studies of skeletal muscle was published by Ringleb et al. (2007) and descriptions of progress in muscle MRE research was also included in more general reviews (Mariappan et al., 2010; Glaser et al., 2012). More recently, Green et al. (2012) performed MRE at a single frequency to measure changes in skeletal muscle following eccentric exercise and reported values for the so-called storage (G') and loss (G'') moduli.

At Charité - Universitätsmedizin Berlin, Klatt et al. (2010) performed the first MRE study of skeletal muscle using multiple actuation frequencies and applied a spring-pot model to these data to derive two viscoelastic constants, $\mu$ and $\alpha$, and study their behavior during a muscle loading paradigm. Working in the same laboratory Papazoglou et al (2012) reported the development of the so-called MDEV technique which uses multi-frequency MRE acquisitions so as to perform high resolution MRE mapping of the magnitude of the shear modulus, $|G^*|$, and phase angle of the shear modulus, $\phi$, and which was illustrated in the study of the human brain.

**RESULTS AND DISCUSSION:**

In this laboratory since 2010 we have pursued a research collaboration with the MRE research group at Charité - Universitätsmedizin Berlin, Germany. We have applied MRE to study the change in thigh muscle stiffness during a straight leg raise paradigm in combination with functional Magnetic Resonance Imaging (fMRI) (Kennedy et al., 2012). Subsequently, a more detailed analysis of the changes in thigh muscle visco-elastic properties was performed using MRE-based statistical parametric mapping (Barnhill et al., 2013). We have also developed techniques for rapid phase correction of MRE data and in-line inversion on a 3T Verio MRI system (Siemens Medical Systems, Erlangen, Germany) (Barnhill et al., 2014 a and b) and demonstrated the application of this Elastography Software Pipeline (ESP) for studying muscle contraction in real-time. More recently, the above mentioned data analysis techniques, together with MDEV, are available in a new MRE data analysis software called the Elastography Software Library (ESL) (Barnhill., 2015). We have used ESL to study age related changes in muscle stiffness (Kennedy et al., 2013) and to perform the first MDEV study of skeletal muscle following an Exercise Induced Muscle Damage (EIMD) paradigm observing that stiffness of the rectus femoris muscle is greatest when high signal is present on T2 weighted MR imaging (Kennedy et al., 2015). Results were also compared with those obtained using a high resolution EPI spiral MRE sequence (Johnson et al., 2013). ESL also includes the first algorithms to enable super-resolution MRE (Barnhill et al., 2015).

**CONCLUSION:**

The new ESL data analysis software provides resources to enable the application of robust measurement techniques in a wide range of MRE studies of skeletal muscle. Examples include real-time functional imaging of muscle contraction as performed by a subject in the MRI scanner, high resolution imaging of tissue visco-elastic properties using multi-frequency MDEV based statistical parametric mapping, and super-resolution imaging for Radiological reporting.

## REFERENCES:


Barnhill, E. Elastography Software Library (ESL) for Magnetic Resonance Elastography. University of Edinburgh (2015).

Barnhill, E., Kennedy, P., Brown, C., van Beek, E. and Roberts, N. Real-time MR elastography of contracted skeletal muscle. Poster presentation, European Congree of Radiolgy (ECR) (2014a).

Barnhill, E., Kennedy, P., Hammer, S., van Beek, E.J., Brown, C. and Roberts, N. Statistical mapping of the effect of knee extension on thigh muscle viscoelastic properties using Magnetic Resonance Elastography. Physiological Measurement, 34, 1675-1698 (2013).

Barnhill, E., Kennedy, P., Johnson, C.L., Mada, M. and Roberts, N. Real-time 4D phase unwrapping applied to Magnetic Resonance Elastography. Magnetic Resonance in Medicine, doi: 10.1002/mrm.25332. [Epub ahead of print] (2014b).

Barnhill, E., Sack, I., Braun, J., Wu□rfel, J., Brown, C., van Beek, E. and Roberts, N. Stationary Super-Resolution Multi-Frequency Magnetic Resonance Elastography (SSR-MMRE) of the Human Brain. Oral presentation, Twenty Third Annual Meeting of the International Society for Magnetic Resonance in Medicine (ISMRM), Toronto, Canada (2015).

Bensamoun, S.F., Glaser, K.J., Ringleb, S.I., Chen, Q., Ehman, R.L. and An, K.N. Rapid Magnetic Resonance Elastography of muscle using one-dimensional projection. Journal of Magnetic Resonance Imaging, 27, 2083-1088 (2008).

Chen, Q., Bensamoun, S., Basford, J.R., Thompson, J.M. and An, K.N. Identification and quantification of myofascial taut bands with Magnetic Resonance Elastography. Archives of Physical Medicine and Rehabilitation, 88, 1658-1661 (2007).

Glaser, K.J., Manduca, A., Ehman, R.L. Review of MR elastography applications and recent developments. Journal of Magnetic Resonance Imaging, 36, 757-774 (2012).

Green, M.A., Sinkus, R., Gandevia, S.C., Herbert, R.D. and Bilston, L.E. Measuring changes in muscle stiffness after eccentric exercise using elastography. NMR in Biomedicine, 25, 852-858 (2012).

Johnson, C.L., McGarry, M.D., Van Houten, E.E., Weaver, J.B., Paulsen, K.D., Sutton, B.P., Georgiadis, J.G. Magnetic Resonance Elastography of the brain using multishot spiral readouts with self-navigated motion correction. Magnetic Resonance in Medicine, 70, 404-412 (2013).

Kennedy, P., MacGregor, L., Barnhill, E., Cooper, A., Hiscox, L., Brown, C., Braun, J., Sack, I., van Beek, E., Hunter, A., Johnson, C.L. and Roberts, N. Mechanical properties and force output of quadriceps muscle following eccentric exercise. Poster presentation, Twenty Third Annual Meeting of the International Society for Magnetic Resonance in Medicine (ISMRM), Toronto, Canada (2015).

Kennedy, P., Semple, S., Gray, C., Cooper, A., Barnhill, E., Queripel, L., Brown, C., Donaldson, D., van Beek, E.J.R., Hoskins, P., Sack, I., Braun, J., Klatt, D., Greig, C., Hunter, A., and Roberts N. Investigation of Human quadriceps variation on resting muscle stiffness and brain activation during contraction. Poster presentation, Twentieth Annual Meeting, International Society for Magnetic Resonance in Medicine (ISMRM), Melbourne, Australia (2012).

Kennedy, P., Semple, S., Gray, C., Barnhill, E., van Beek, E.J.R., Roberts, N., and Greig, C. Magnetic Resonance Elastography measurement of human skeletal muscle stiffness shows a decline in older adults compared with young. Thirty Seventh World Congress of the International Union of Physiological Sciences (IUPS), Birmingham, UK (2013).

Klatt, D., Papazoglou, S., Braun, J. and Sack, I. Viscoelasticity-based MR elastography of skeletal muscle. Physics in Medicine and Biology, 55, 6445-6459 (2010).

Mariappan, Y.K., Glaser, K.J. and Ehman, R.L. Magnetic Resonance Elastography: a review. Clinical Anatomy, 23, 497-511 (2010).

Papazoglou, S., Hirsch, S., Braun, J. and Sack, I. Multifrequency inversion in Magnetic Resonance Elastography. Physics in Medicine and Biology, 57, 2329-2346 (2012).

Ringleb, S.I., Bensamoun, S.F., Chen, Q., Manduca, A., An, K.N. and Ehman, R.L. Applications of Magnetic Resonance Elastography to healthy and pathologic skeletal muscle. Journal of Magnetic Resonance Imaging, 25, 301-309 (2007).