MR Gravimetry (MRG) of the Lung

Oliver Bieri[1]

[1]*Department of Radiology, Division of Radiological Physics, University of Basel Hospital, Basel, Switzerland*

Target audience. Physicists and physicians interested in lung imaging methods.

Purpose. Computer tomograms show vertical gradients in parenchyma density due to gravity, relating to the mechanical properties of the lung [1]. Gravitational effects on the lung were also assessed by a few occasional MRI studies [2,3], but are generally limited by the overall poor SNR of contemporary methods. Only recently, a new ultra-fast balanced SSFP (bSSFP) imaging technique was introduced, offering exceptional SNR and CNR for in vivo lung imaging at 1.5 T [4]. This makes the investigation of gravity-related effects in the lung tissue feasible. Here, we develop the corresponding framework for such MRI investigations, hence termed MR Gravimetry (MRG) of the lung.

Methods. MRG of the lung was investigated using a dedicated MR setup: to this end, the body coil was used for transmission and reception, instead of multi-array receive arrays, to mitigate large-scale coil sensitivity issues. The 3D ultra-fast bSSFP scan was performed with a 2.5 mm isotropic resolution, yielding a TR of 1.08 ms, guaranteeing lung tissue imaging within the passband of bSSFP to avoid gross signal modulations due to large-scale B0 field inhomogeneities. Scans were performed in both supine and prone position to reverse the action oft the gravitational field with respect to the body position, i.e. lung morphology. Scans were performed in a single breath-hold and in full expiration and inspiration to modulate alveolar pressure, and thus the overall impact of gravity on the self-mass distribution of the lung under equilibrium condition.

Theory. It is assumed that the lung compresses under its self-weight, similar to the self-mass distribution of a "slinky" in equilibrium (see Fig. 1): at any position along the spring, the local repulsive tension, dF_k, balances the gravitational force, dF_G, from the cumulative self-mass of the elements (d*m*) underneath it. The overall variable external tension, i.e. alveolar pressure, (modeled by the mass *M*) leads to an elongation of the spring with mass m to the length *z*, as compared to its unstretched length z_0. Formally, the equilibrium density, $\lambda := m/z$, of the spring with spring constant k and under the action of gravity (*g*) is given by [5]:

$$\lambda(\zeta) = \left(\left(\lambda_0^{-1} + \rho\gamma_0 \right)^2 - 2\gamma_0 \zeta \right)^{-1/2}, \text{where } \zeta := \frac{z}{z_0}, \lambda_0 := \frac{m}{z_0}, \rho := \left(1 + \frac{M}{m} \right), \gamma_0 := \frac{g}{k} \qquad [1]$$

It is interesting here to note that, in this model, the breathing position (i.e., expiration & inspiration) modulates the mass *M* (and thus ρ), whereas the other parameters (λ_0 and γ_0) remain constant. Here, in a first step, a nonlinear global least-squares fitting routine was used to evaluate a parametric form of Eq. [1] for variable breathing positions, that is, in expiration using $\lambda_{exp}(d) = (p_1^2 - p_3 \cdot d)^{-1/2}$ and in inspiration using $\lambda_{ins}(d) = (p_2^2 - p_3 \cdot d)^{-1/2}$, where *d* is the distance counted in voxels.

Results & Discussion. The mean lung signal variation was derived from sagittal expiration and inspiration views in supine (Fig. 2) and prone (Fig. 3) position along the direction of gravity, and subsequently fitted to Eq. [1]. In supine position, we find $p_{1s} = 0.0191 \pm 0.0004$, $p_{2s} = 0.0284 \pm 0.0005$, $p_{3s} = 6.5\text{E-}6 \pm 0.3\text{E-}6$, whereas in prone position, we find $p_{1p} = 0.0168 \pm 0.0004$, $p_{2p} = 0.0263 \pm 0.0007$, $p_{3p} = 5.0\text{E-}6 \pm 0.3\text{E-}6$. Overall, good correspondence between the model and the vertical lung signal variation is observed. Generally, however, $p_3 \sim g/(k \cdot z_0)$ appears to be reduced by about 25% in prone as compared to the supine position, but is expected to be unaffected by body position. In contrast, $\Delta p_{(s,p)} := p_{2(s,p)} - p_{1(s,p)} = \rho\gamma_0$ depends on the alveolar pressure (*M*), but $\Delta p_{(s)} \approx \Delta p_{(p)}$ indicating similar end-expiratory and end-inspiratory breathing positions in both body positions. Clearly, these findings require further in-depth investigation, but point towards a conceptual new framework for the investigation of intrinsic lung mechanical properties under the action of gravity with MRI.

Conclusion. MRG of the lung represents a new approach to address the self-mass distribution of the lung tissue under equilibrium conditions. The extracted parameters from the spring model relate to lung mechanics, and may thus represent a highly sensitive measure to global and local changes in the strain constraints, such as for instance in COPD.

References. [1] Millar AB et al. Thorax 1989; 44:485-490. [2] Mayo JR et al. J Thorac Imaging. 1995; 10:73-81. [3] Keilholz SD et al. Magn. Reson. Imag. 2001; 19: 929-935. [4] Bieri O. Magn Reson Med. 2013 doi: 10.1002/mrm.24858. [5] Edwards TW & Hultsch RA. Am. J. Physics. 1972; 40: 445-449.

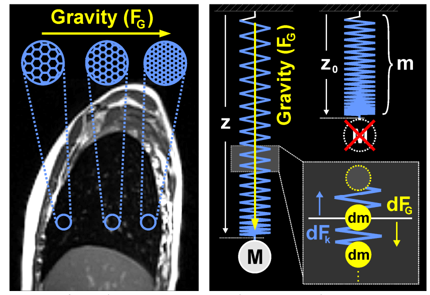

Fig. 1: (left) Presumed parenchyma tissue density variation due to gravity. (right) Lung tissue spring model (for details, see text).

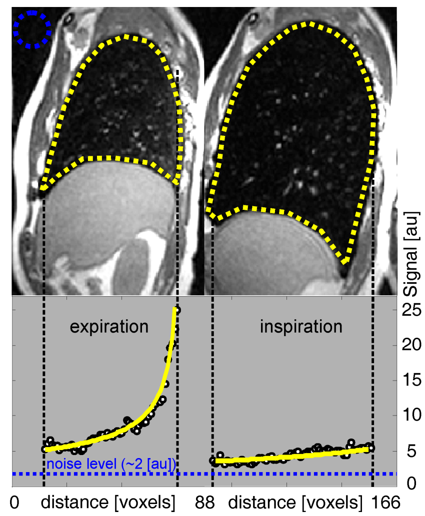

Fig. 2: Lung signal gradient observed in supine position and corresponding fit (yellow line).

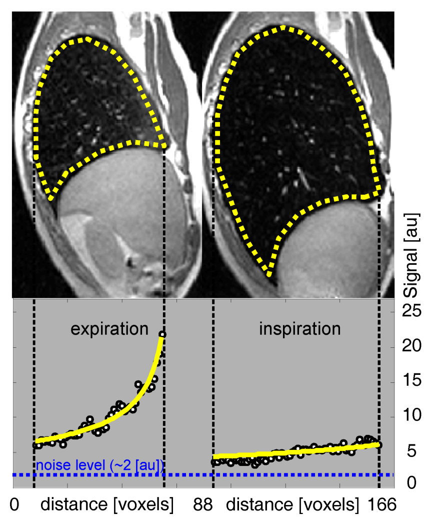

Fig. 3: Lung signal gradient observed in prone position and corresponding fit (yellow line).