MR-Elastography for Breast Lesion Characterization - The Effect of Rheology on its Diagnostic Impact -

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Introduction

The stress-strain relationship in frequency domain is written as $\sigma(\omega)=G^*(\omega)*\varepsilon(\omega)$ when considering linear isotropic viscoelasticity. Thus, a MRE measurement performed at a single frequency ω_0 provides at most one complex number $G^*(\omega_0)=G_d(\omega_0)+iG_l(\omega_0)$, which is denoted as the complex shear modulus with G_d the dynamic modulus and G_l the loss modulus. Full understanding of the underlying rheological model is only possible if measurements are done at various frequencies because G_d and G_l are frequency dependent in tissue [1,2]. Interpretation of these two moduli in terms of truly constant material parameters (elasticity E and viscosity η) depends strongly upon the assumed rheological model. For instance, the classical Voigt model (spring and dashpot in parallel) allows a very simple interpretation, i.e. $G_d=E^{Voigt}$ and $G_l=\omega\eta^{Voigt}$. Here, the dynamic modulus is equal to the elasticity and independent of frequency, and the loss modulus rises with frequency according to a power-law $\sim\omega^\alpha$ with exponent $\alpha=1$. This, however, is not what has been measured in tissue [3]. The Maxwell model can be used to interpret the data in terms of an instantaneous elasticity, i.e. the high frequency limit denoted as the glassy region. This is opposite to the Voigt model whose elastic component represents the low frequency limits (the so-called rubbery region). Tissue, however, exhibits scaling properties, i.e. G_d and G_l rise according to a power-law $\sim\omega^\alpha$ with $\alpha\in(0,1)$. Such behavior is described by a so-called springpot whose rheological interpretation is a fractal structure consisting of classical elements (Fig.1a) [4]. The topological organization of the network is reflected by the exponent of the power-law: low values resemble strong entanglement while high values indicate loose connections [5].

Materials & Methods

3D steady-state MR-Elastography is performed within full clinical environment. Data are obtained at 85Hz mechanical excitation frequency with an isotropic resolution of $(2mm)^3$ within about 10min of total acquisition time after clinical MR-mammography using Magnevist® as contrast agent [6]. 33 patients with malignant tumors and 18 patients with benign lesion were examined. Reconstruction was performed according to [7]. Once maps of G_d and G_l were obtained, the average values of E and η within the lesions were calculated according to the rheological model under investigation.

Results

Fig.1b) shows the subtraction image for a patient with two malignant lesions. The corresponding image of E^{Voigt} (Fig.1c) fails to show the lesions while they are clearly visible at their correct locations in the map of $E^{Maxwell}$ (Fig1d). This disability of the Voigt model to properly classify the data in terms of its elastic component is also reflected by the mean values of E^{Voigt}: malignant tumors $E^{Voigt}_{mean}=2.2\pm1.2$ kPa and benign lesions $E^{Voigt}_{mean}=1.7\pm1.0$ kPa, i.e. strongly overlapping distributions. Contrary, utilization of the Maxwell model yields for the mean values of $E^{Maxwell}$: malignant tumors $E^{Maxwell}_{mean}=8.0\pm5.7$ kPa and benign lesions $E^{Maxwell}_{mean}=3.0\pm2.1$ kPa, i.e. well separated distributions. Fig. 1e) shows the distributions of the two groups in a scatter-plot, where the x-axis represents $E^{Maxwell}$ [kPa] and the y-axis the exponent β according to the springpot model with $G_l/G_d=\tan(\beta*\pi/2)$.

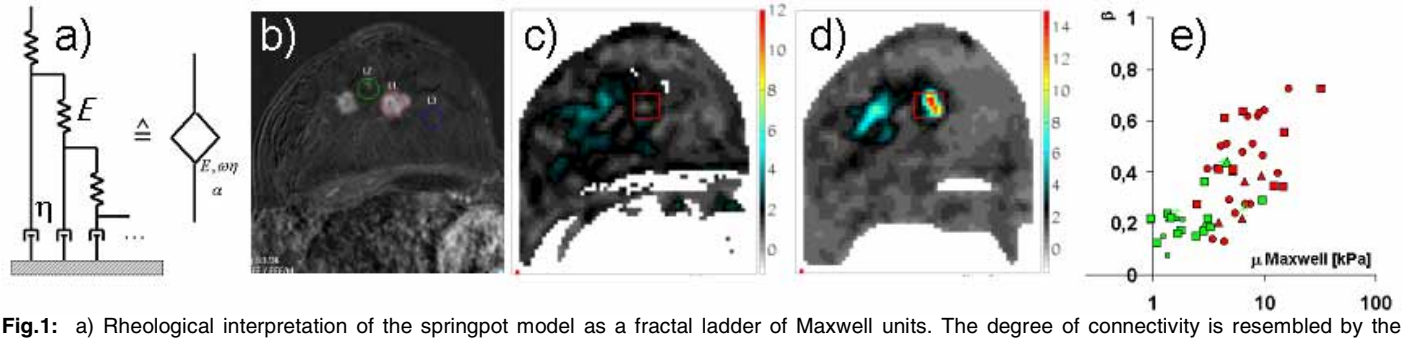

Fig.1: a) Rheological interpretation of the springpot model as a fractal ladder of Maxwell units. The degree of connectivity is resembled by the exponent of the power-law, i.e. β. b) MRM subtraction image w/o contrast agent depicting the location of two tumors (LCIS). Reconstructed maps of c) E^{Voigt} and d) of $E^{Maxwell}$ in units of [kPa]. e) Compilation of the clinical results in a 2D scatter-plot (red markers=malignant tumors, green markers=benign lesions). Here, $E^{Maxwell}$ is plotted versus β.

Discussion & Conclusions

The disability of the classical Voigt model to explain the dispersion relation of $G^*(\omega)$ for soft tissue has already been recognized for a long time. Here, we demonstrate that ignoring the intrinsic relationship between loss modulus and dynamic modulus (established via causality, i.e. the Kramers-Kronig relations) might easily lead to results which are physically correct but not meaningful in terms of diagnostic added-value. The true underlying rheology of each individual tumor can only be obtained by measuring $G^*(\omega)$ in a sufficiently large frequency interval. This is subject to current clinical investigations. From the mono-chromatic data presented in this study it is obvious that interpreting the elastic component in terms of the Maxwell model provides far better separation between benign and malignant lesions. Thus, it seems that the glassy plateau reveals more insight into the architecture of tumors than the lower frequency limit. Moreover, interpretation in terms of the springpot model yields information about the degree of cross-linkage: malignant tumors populate the high β region indicating a more loosely connected liquid-like architecture; benign lesions exhibit mainly low values of β thus representing tightly connected solid-like structures [7].

References

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