Original Research

Towards Compression-Sensitive Magnetic Resonance Elastography of the Liver: Sensitivity of Harmonic Volumetric Strain to Portal Hypertension

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Purpose: To assess induced oscillating volumetric strain as a biomarker for intrahepatic blood pressure abnormalities.

Materials and Methods: Harmonic vibrations of 25 and 50 Hz frequency were induced in the liver and measured by fast 3D vector field magnetic resonance elastography (MRE), followed by processing of the decomposed curl (shear) and divergence (compression) fields. After an initial study on an excised sheep liver, a group of 13 patients with hepatic hypertension were examined before and after implantation of a transjugular intrahepatic portosystemic shunt (TIPS).

Results: In the sheep liver specimen, volumetric strain decreased with excess portal pressure, whereas shear strain was not sensitive to portal pressure. In the patient cohort, volumetric strain was significantly higher after TIPS placement ($P = 1.38 \cdot 10^{-5}$), while neither shear strain nor the shear modulus were affected. Normalized changes in volumetric strain were significantly correlated with the hepatic venous pressure gradient ($R^2 = 0.7258$, $P = 6.95 \cdot 10^{-5}$) and portal venous pressure ($R^2 = 0.5028$, $P = 0.0016$).

Conclusion: These results indicate for the first time the sensitivity of volumetric strain to symptomatically high values of tissue pressure and motivate further developments in compression-sensitive MRE and poroelastography towards image-based and noninvasive markers of tissue pressure.

Key Words: magnetic resonance elastography; MRE; volumetric strain; pressure; compression modulus; divergence; liver; portal hypertension; pressure gradient; TIPS; portosystemic shunt

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ONE QUARTER TO ONE THIRD of hepatic volume is blood. The liver is supplied by two intricate vascular circuits: the arterial system for maintenance of vital functions of the liver and the portal venous system for clearing hormones and metabolites from the blood. Both systems interact closely through classic arterial autoregulation and hepatic arterial buffer response (1). The two intrinsic regulatory mechanisms maintain total hepatic blood flow at a constant level, thus stabilizing liver function and metabolic homeostasis (2).

The hepatic vascular flow response is of special importance since there is no regulatory mechanism at the level of the portal vein. The liver receives all the blood that arrives in the portal vein from the prehepatic vasculature (3). As a consequence, hepatic vasculature is highly susceptible to hypertension in subjects with diseases that affect the compliance of the hepatic vascular bed, such as hepatic fibrosis and cirrhosis (4). As a result of the increase in portal pressure, portal blood flows through portosystemic collaterals, thus bypassing the liver and promoting the formation of variceal veins. To assess portal hypertension and dysfunctional portosystemic flow, imaging modalities capable of measuring pressure and hemodynamics are highly desired (5).

Considering hepatic tissue as a biphasic system constituted by a solid tissue matrix and a fluid-filled vascular tree, effective mechanical properties of the liver arise from the interaction between vascular mechanics and soft tissue matrix properties. Elastography can measure the effective mechanical parameters in vivo (6,7). In the liver, the effective shear modulus, which is the resistance of the tissue to shear deformation, is increasingly used as a new biomarker for liver fibrosis (8–13). Given the high volume

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