Magnetic Resonance in Medicine 50:220–222 (2003)

Electromagnetic Actuator for Generating Variably Oriented Shear Waves in MR Elastography

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Magnetic resonance elastography (MRE) is a recently developed technique for determining the mechanical properties of biological tissue. In dynamic MRE, electromagnetic units (actuators) are widely used to generate shear waves in tissue. These actuators exploit the interaction between the static magnetic field B_0 and an annular coil supplied with alternating currents. Therefore, coil movements are restricted to selected orientations to B_0. Conventional actuators transfer this movement collinearly to B_0 into the tissue. In this study, an electromagnetic actuator was introduced that overcomes this limitation. It is demonstrated that different directions of mechanical excitation can be generated and monitored by MRE. Different spatial components of the propagation of the shear waves were determined using agarose phantoms. The technique allows maximum contrast for MRE images of objects with anisotropic strain components such as muscle tissue. Magn Reson Med 50:220–222, 2003. © 2003 Wiley-Liss, Inc.

Key words: MR elastography; electromagnetic actuator; shear waves; anisotropic elasticity

Dynamic MR elastography utilizes the fact that the shear wave propagation in biological tissue is related to material stiffness (1–3). Stiffness parameters such as the shear modulus may serve to distinguish between healthy and pathologic tissues (3–5). In dynamic MRE, mechanical excitation of tissue is synchronized with phase-sensitive acquisition techniques (6). The recorded wave images show solely signal components related to tissue oscillations. In vivo, shear waves are applied by an oscillating transducer fixed to the surface of the body. The frequency range varies between 50 and 500 Hz. Electromagnetic actuators (1–3,7,8) and piezoelectric devices (9,10) have been employed as mechanical excitation units. Although the latter can be positioned in arbitrary orientations with respect to B_0, the construction is quite elaborate and time-consuming. Electromagnetic actuators are easier to construct, cost less, and can be customized easily to account for special in vivo applications such as muscle, breast, or brain MRE (11,12). Applying alternating currents to an annular coil generates motion. A maximal torque acts on the coil if the normal vector of its plane is perpendicular to B_0. The resultant periodic tilt is transformed for mechanical actuation using a pivoted rod. In this commonly used design, the orientation of the actuator coil restricts the directions available for mechanical excitation. For isotropic tissue, the direction of shear wave displacement has no influence on the determination of the shear modulus. However, in anisotropic tissue such as skeletal muscles (7,8) or pathologic tissue (3), the propagation speed of the shear waves should be determined in different spatial directions. In these cases, actuators with a variable direction of excitation are required to gain full information about tissue characteristics.

In this study, an electromagnetic actuator is introduced that allows harmonic excitations with directions between 0° and 90° to the B_0 field to be generated. To demonstrate the feasibility of the new actuator, experiments on agarose phantoms are presented and compared with the performance of a conventional electromagnetic actuator. Displacement components parallel and orthogonal to the B_0 field are compared for the conventional and the new actuator.

MATERIALS AND METHODS

Construction of the Actuator Unit

Figure 1a shows a schematic of a conventional actuator design. For clarity, a coordinate system is introduced where the z-axis is collinear to B_0. The normal vector to the plane of the actuator coil [1] must be oriented perpendicularly to B_0. A carbon fiber tube [2] connects the coil with the excitation plate [5], which is positioned on the surface of the object under investigation. Applying an alternating current results in periodic oscillation of the coil around the x-axis. This motion is transferred by an axis [3] mounted on a base plate [4] and mechanically linked with the tube [2]. This construction allows shear wave excitation only parallel to B_0. The new actuator design (Fig. 1b) results from adding a pivoted redirection plate [6] connected with the tube carrying the actuator coil. The axis between the pivot point [8] and the connecting point of the tube [7] lies perpendicular to the tube's plane of motion. The redirection of the initial motion is determined by the angle between the connecting point of the tube [7], the pivot point [8], and the inserting point of the excitation plate [9]. An angle of 90° (Fig. 1b) results in a shear wave excitation perpendicular to B_0. Other angles can be chosen by varying the position of the excitation plate in the different inserting points. Figure 1c shows a cross section of the actuator and details of the connection between tube [2] and redirection plate [6]. A ball-shaped head made of brass was securely fitted into the plate. The head of the ball [11] was pressed into a Teflon cylinder [10] fixed with a bushing [12] to the tube to form a gimbal joint.

Methods

Data were acquired on a 1.5 T scanner (Siemens Magnetom Vision, Erlangen, Germany). A modified echo planar im-

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Grant sponsor: the Ernst Schering Research Foundation (to I.S.).

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Received 9 August 2002; revised 14 February 2003; accepted 14 February 2003.

DOI 10.1002/mrm.10479

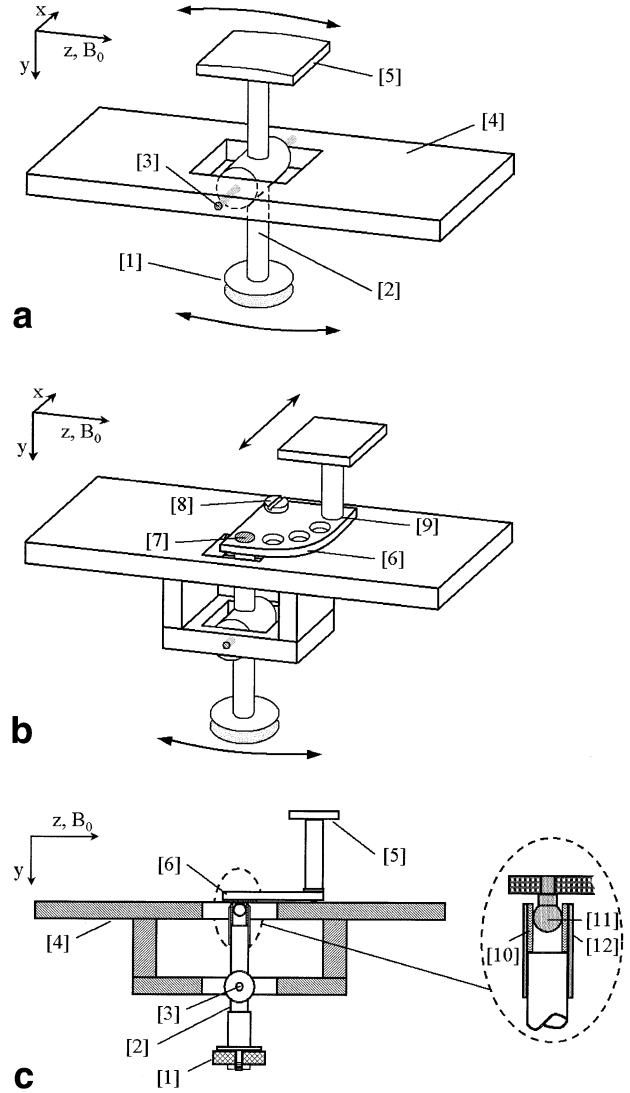

FIG. 1. Design of electromagnetic actuators. **a:** Conventional actuator. Owing to the direct motion transfer, a mechanical excitation is only possible parallel to B_0 (z-direction). See text for further details. **b:** Bottom view of the new redirection actuator. A variable direction change of motion is achieved with an additional pivoted redirection plate [6]. The plate is connected with a standard actuator mounted piggyback onto an adapted base plate. See text for details. **c:** Cross section of the redirection actuator showing details of the drive of the redirection plate; for details, refer to text.

aging sequence (11) was used for data acquisition (repetition time: 2 sec; effective echo time: 113 ms; field of view: 220 mm; matrix size: 96 × 128). Trapezoid-shaped motion-sensitizing gradients G_M (25 mT/m, risetime of 600 μs) were capable of being applied in any direction. Actuators were fixed with Velcro strips to a standard head coil. Eleven sinusoid-shaped wave cycles were applied for mechanical excitation; the last four were motion encoded. All experiments were performed on an agarose gel phantom (1.5% agarose in water). Excitation amplitudes were measured optically by deflecting a laser beam. The frequency of mechanical excitation was 200 Hz. Postprocessing of data was performed using MatLab® R13 (MathWorks, Natick, MA, USA).

RESULTS

In the present study the redirection of excitation takes place on a circular path with a radius of 40 mm and a maximum displacement of 0.41 mm in x-direction. Motion components parallel and perpendicular to B_0 (main in x and transverse in z-direction) were determined (Fig. 2) for a mechanical excitation in x-direction. Figure 2 compares the excitation components of the main direction of the conventional and the redirection actuator with the remaining orthogonal components. In Fig. 2a, acquired with the redirection actuator perpendicular to B_0, mechanical excitation and G_M are oriented in x-direction. The shear waves propagate with high amplitude (bright and dark gray values) from the top to the bottom of the phantom. By reorienting G_M in z-direction (Fig. 2b), the transverse motion component was determined as a speckled pattern exhibiting lower amplitude. Using identical settings, data were acquired using a conventional actuator (Figs. 2c,d). G_M and mechanical excitation were applied collinearly to B_0 in z-direction. The wave pattern observed for the main motion component is comparable to that in Fig. 2a. The intensity is about 2.5 times lower than that in Fig. 2a. Switching G_M to x-direction and keeping the mechanical excitation in z-direction (Fig. 2d) results in very weak wave amplitudes for the transversal motion component. The gray scale bar at the bottom relates gray values to the particle displacement. The ratios between the main motion components (x for the redirection unit and z for the conventional actuator) and the transversal components are shown in Fig. 3. The ratios base on signal intensities that have been calculated as mean over the whole image and change comparably for both types of actuators to a nearly identical limit as a function of the overall displacement in the direction of the main motion component.

DISCUSSION

The new redirection actuator allowed the generation of shear waves orthogonal to B_0 with displacement amplitudes that were about 2 times higher than those of a conventional actuator. This difference may be explained by small variations in the impedance of the actuator coils and by differing quantities of lever ratios between the actuators.

The redirected motion follows a weakly curved path that imposes a certain amount of motion components transversely to the main deflection. Regarding the maximum displacement of 0.41 mm, as was achieved using the redirection actuator, the intrinsic transverse motion components were not expected to exceed 0.5% of the main displacement. Experimentally, a higher fraction of transverse motion was found. This indicates deviations from the ideal motion characteristics of the excitation plate. Similar nonideal mechanical characteristics were found for a conventional actuator as indicated by the leveling of the ratios of motion components shown in Fig. 3. For this type of actuator, the transverse motion components were expected to be zero. Thus, the nonideal vibration components are due to the pivoted rod or to a limited rigidity of the restraint of the base plate of the actuators fixed by Velcro tapes to the MR acquisition coil, rather than imposed by the redirection mechanics of the new actuator design.

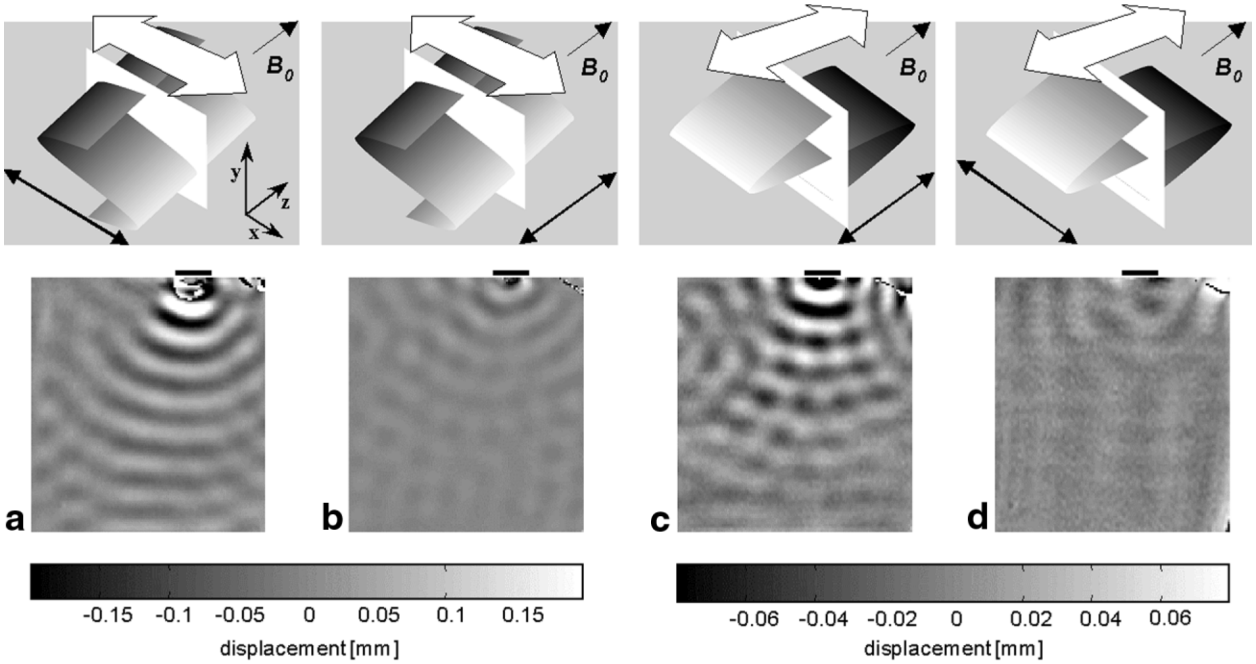

FIG. 2. Comparison of the motion characteristics of the conventional and the redirection actuator. MRE data were acquired for excitation components parallel and orthogonal to B_0 (main and transverse). Upper row: Correlation of the directionality of particle displacement (sine wave), mechanical excitation (bold white arrows), and motion-encoding gradients (G_M, black arrows). Corresponding experimental shear wave patterns are shown in the lower row (200 Hz excitation frequency). The position of the excitation plate (size: 1 cm^2) is indicated as a bar on the top of the phantom. **a,b:** Redirection actuator, mechanical excitation orthogonal to B_0 (*x*-direction). **a:** G_M in *x*-direction shows shear waves with high amplitude; **b:** G_M in *z*-direction results in waves with low amplitude. **c,d:** Conventional actuator, mechanical excitation in *z*-direction. **c:** G_M in *z*-direction gives an image comparable to **a**; **d:** G_M in *x*-direction shows waves with low amplitude. The gray-scale bars at the bottom define the particle displacement displayed in the images.

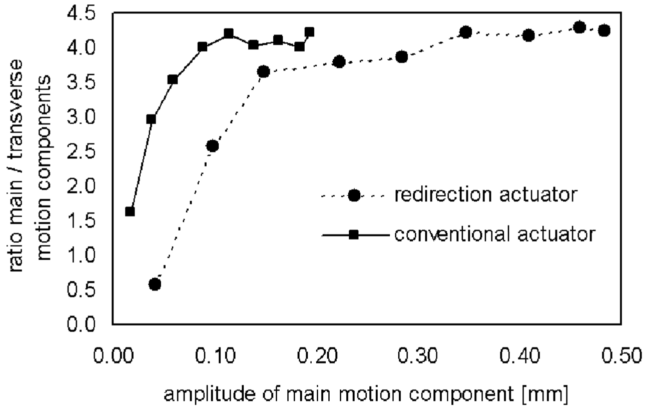

FIG. 3. Ratios of the wave amplitudes along the main displacement direction to the transverse motion components for the redirection and the conventional actuator as a function of the overall displacement observed for the main motion component.

As the presented actuator allows a variable direction of excitation from parallel to orthogonal to B_0, it is well suited for use in forthcoming studies of the anisotropic elastic properties of tissues such as muscle.

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