Potential MR hazard to patients with metallic heart valves: the Lenz Effect

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Introduction
Concern has long been expressed about the possible adverse electromagnetic interactions between mechanical heart valves and MR systems (Soulen et al 1985). Studies have focused on heating and direct current induction due to RF, and deflection of the ferromagnetic components due to the high magnetic field. Maximum deflection forces up to $6.2 \times 10^{-3} \text{N}$ were measured on one such valve at 1.5T, though even this has not been regarded as significant (Shellock 1999). However one mechanism for physical interaction between MRI and metal containing heart valves has not, to our knowledge, been considered. This is the induction of currents on metal components moving through the static field. Lenz’s Law states that: 'the direction of the induced emf is such that any current it produces tends to oppose the change of flux' ie its motion will be retarded. This effect can be easily demonstrated on any high field system using a non-ferromagnetic metal object such as an aluminium plate. Objects which would normally take less than a second to fall over will take almost a minute to do so in a 1.5T magnet due to this retarding effect.

In this paper the basic theory of this interaction is described and a simple model is used to estimate the maximum forces experienced by the metal strengthening ring of a tilting disc heart valve, under a range of valve opening times.

Theory

An electric conductor forms a circuit in a uniform static magnetic field ($B_0$). If the magnetic flux ($F$) through the closed path varies with time ($t$) due to the movement of the circuit then a current is induced. From the Faraday-Henry Law of electromagnetic induction the induced current ($I$) in such a resistive circuit (resistance $R$) will be:

$$I = \frac{-1}{R} \frac{dF}{dt} \quad [1]$$

If this conductor has an area $S$ it will have a magnetic dipole moment

$$M = IS \quad [2]$$

and so experience a torque ($T$) in field $B_0$ of:

$$T = MB_0 \sin A \quad [3]$$

where $A$ is the angle between the conductor and the magnetic field. Substituting in to [3] gives the torque on the circuit as:

$$T = \frac{\rho S_X}{L} \frac{dF}{dt} \sin B_0 \sin A \quad [4]$$

where $S_X$ is the cross-sectional area of the wire, $L$ its length and $\rho$ its conductivity.

Model

Single leaflet tilting valves open to a maximum of 75 degrees and range in diameter up to 39mm. The rate of change of orientation of the valve changes markedly over the cardiac cycle, but the maximum change occurs during valve opening which should take less than 50ms to be completed if the valve is to mimic the function of normal heart valves. Opening times of 10, 20, 30, 40 and 50ms will be considered.

We will assume that the strengthening ring is made of titanium (as in the Cross-Jones valve and Starr-Edwards Model 6520), that the diameter of the metal is 1mm and that the conductivity of titanium is $2.5 \times 10^7 \text{Ohm}^{-1} \text{m}^{-1}$.

Results

The following Table shows the theoretical values of the torque, force and resistive pressure experienced by 39mm diameter rings of titanium embedded in a solid disc for different opening times at 1.5T. It should be noted that whilst torque is related to the cube of the radius of the ring, and force to the square of the radius, the pressure is independent of the radius. The pressure figures estimated vary with opening time and the metal used for the ring, but will be the same whatever the diameter of the disc.

<table>
<thead>
<tr>
<th>Opening time (ms)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque (Nm)</td>
<td>0.048</td>
<td>0.024</td>
<td>0.016</td>
<td>0.012</td>
<td>0.010</td>
</tr>
<tr>
<td>Force (N)</td>
<td>1.231</td>
<td>0.616</td>
<td>0.410</td>
<td>0.308</td>
<td>0.246</td>
</tr>
<tr>
<td>Resistive Pressure</td>
<td>7.7</td>
<td>3.9</td>
<td>2.6</td>
<td>1.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Discussion

Heart valves open in response to pressure gradients across them. The typical peak pressure difference for the aortic valve is 30 to 40 mmHg. The mitral valve must however open under a pressure difference of only a few mmHg (range 0.96 to 3.5 mmHg).

Assuming the 'worst case' ie opening time of only 10ms (opening times of 20-30ms are probably more realistic) produces forces approximately 180 times larger than the maximum force previously experimentally measured on a metallic heart valve due to the interaction between its ferromagnetic components and the static field (Soulen 1985). It must be stressed that these reverse pressure effects will increase linearly with field strength, doubling to 15mmHg at 3T. Clearly the Lenz effect on tilting metal-containing discs needs to be investigated further as such pressures have the potential to represent a hazard to patients with such implants.

It should be noted that similar effects will occur when the disc itself is made of metal but that the caged ball type of valve (eg Starr-Edwards Model 2320) will not suffer retardation as the ball experiences no net flux change during its motion (in the homogeneous centre of the magnet at least).

Conclusions

The theoretical analysis presented in this paper suggests that potential hazards may exist for patients with heart valve discs which contain metal components. Experimental studies should be performed to verify this analysis. Additional monitoring or even exclusion should be considered for patients with such valves, particularly at higher field strengths and/or if the valve is in the mitral position.

References
Shellock F. (Letter) JMRI 1999;10:107