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Estimation of resistive pressure effects in mechanical heart valves due to MRI

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Introduction

Mitral and aortic valve replacement is a procedure which is common in cardiac surgery. Some of these replacement valves are mechanical and contain moving metal parts in the disc or leaflets. When exposed to MRI there is a potentially hazardous interaction between the moving metal parts and the static magnetic field due to the Lenz Effect. The Lenz Effect is a result of the current (induced by the metallic component moving in a static magnetic field) changing as the valve rotates; this causes a secondary field to be set up which opposes the original field and consequently opposes the motion of the component. A simple 'worst case' analysis of the potential hazard has been performed previously (1). However the differential nature of the delaying effect of the motion of the mechanical valve on the Lenz effect itself was not assessed. In this paper a differential model of a ring-strengthener valve type has been developed to take account of the interplay between the Lenz Effect and disc motion.

Theory

It is straightforward to calculate the torques produced by the Lenz Effect on the metallic ring strengthener type of valve for various opening times. However, given the values of torque it is not obvious how the normal motion of the heart is affected. The significance of these results cannot be fully ascertained until the forces due to the Lenz Effect are placed within a suitable model where the impact can be realised numerically. Consequently it is considered how the Lenz force fits into the overall motion of the mechanical heart valve by constructing a differential Newtonian model. The individual forces which are significant are: the Lenz Effect, blood pressure opening and closing the single-leaflet valve, and the viscosity of the blood. We know:

$$F(Lenz)= -(B^2 A^2 /R).\ \sin W(t).\ d(\cos W(t))/dt \qquad [1]$$

where R and A are the radius and area of the valve disc and W is the angle it makes to the field (B).

The overall equation describing the motion of the disc can be shown to be:

$$mW''(t) + ((B^2 A^2 /R).\sin^2 W(t)).W'(t) - F(blood).\cos W(t) - (nA/l)W'(t) = 0 \qquad [2]$$

where n is blood viscosity, l the length it is forced through and m is the mass of the disc.

This has no analytical solution but is solved using numerical methods. The physical parameters come from considering a titanium ring strengthener valve, 39mm in diameter which opens 85 degrees. A fourth-order Runge-Kutta numerical method for integration is used to solve the above equation giving the variation of the opening angle with time. The strength of the external magnetic field can be altered to show the delay time in opening with respect to the normal, i.e. when B=0, opening times for the valves.

Results

The resistive pressure effects on the valve disc as a function of field strength are calculated for valves in the aortic and mitral positions and the results are summarised in Table 1.

Discussion

Generally the important data required to derive the results is not as readily available with the same accuracy as values for resistance or the materials of which the valves are constructed. This fact can be understood given the difficulty of making measurements of the actual pressure differences which instantaneously occur in a particular human heart. This, coupled with the fact that the forces which cause the valves to open vary constantly in one person and even more between individuals means that some upper value must be used to find meaningful results. To that end, the highest likely pressures have been determined from established sources giving information on typical pressures etc. For example, it is known that the heart valves must open in a `few milliseconds´ (2); experiments performed on animals show that the valves generally open in less than 50 ms (3).

The reason no one has yet reported significant difficulty caused by the Lenz Effect could be that the relevant factors have not been in place. That is, no patient with a heart valve with moving metal components has been imaged in an MR system with the optimally bad orientation with relation to the static magnetic field. This does not seem as probable as the argument that the magnetic fields within commercially available MR systems are not of great enough magnitude to produce a significant torque to noticeably impede the motion of the disc.

The results of this paper are in agreement with the `worst case´ model (1) in that both show that the Lenz Effect has the potential to cause the moving metallic components of mechanical heart valves to experience a torque causing a delay in their rotation. However whilst (1) raised the possibility of significant effects at fields even as low as 1.5T, the model in this paper suggests that higher fields are required. At 1.5 Tesla the effect would be less than 1% of the pressure effect for mitral and aortic valves (Table 1). However, 3 to 4.7 Tesla systems are becoming more prevalent and for such field strengths the percentage effect would be up to 9.95% for a valve in the mitral position and up to 9.91% for a valve in the aortic position. Clearly experimental studies are required to establish appropriate maximum field levels for such valves, but it would seem prudent at this stage to exercise caution at fields of 3T and above. Should the torque be significant, and it should be stressed that it could be significant in only the small subset of patients with mechanical heart valves which have moving metal components (ie in the disc or leaflet but not the cage or ring), it would be recognised by symptoms such as breathlessness in the patient and reduced cardiac output. That is, the Lenz Effect could make the heart behave as though it were diseased with the resulting symptoms and difficulties.

References

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2.Guyton, A.C. Textbook of Medical Physiology, pub. W.B. Saunders Company, 1991,
3.Lynch W. 1 Implants (New York: van Vostrund Reinhold)1982

Table 1. The Lenz Effect as a percentage of normal pressure effect

	Mitral	Aortic
Field Strength (T)	Percentage Effect	Percentage Effect
1	0.38	0.38
1.5	0.81	0.88
2.4	2.14	2.31
3	3.48	3.68
4.7	9.95	9.91
7	33.90	26.30
8	60.52	37.17
10	145.10	65.03