Closed bore XMR (CBXMR) systems for aortic valve replacement: Investigation of rotating-anode x-ray tube heat loadability

John A. Bracken^{a)}

Sunnybrook Health Sciences Center, Department of Medical Biophysics, University of Toronto, 2075 Bayview Avenue, Toronto, Ontario M4N 3M5, Canada

Prasheel V. Lillaney and Rebecca Fahrig

Department of Radiology, Lucas MRS Center, Stanford University, 1201 Welch Road, Stanford, California 94305-5488

J. A. Rowlands

Sunnybrook Health Sciences Center, Department of Medical Biophysics, University of Toronto, 2075 Bayview Avenue, Toronto, Ontario M4N 3M5, Canada

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In order to improve the safety and efficacy of percutaneous aortic valve replacement procedures, a closed bore hybrid x-ray/MRI (CBXMR) system is proposed in which an x-ray C-arm will be positioned with its isocenter ≈ 1 m from the entrance of a clinical MRI scanner. This system will harness the complementary strengths of both modalities to improve clinical outcome. A key component of the CBXMR system will be a rotating anode x-ray tube to produce high-quality x-ray images. There are challenges in positioning an x-ray tube in the magnetic fringe field of the MRI magnet. Here, the effects of an external magnetic field on x-ray tube induction motors of radiography x-ray tubes and the corresponding reduction of x-ray tube heat loadability are investigated. Anode rotation frequency f_{anode} was unaffected when the external magnetic field B_b was parallel to the axis of rotation of the anode but decreased when B_b was perpendicular to the axis of rotation. The experimental f_{anode} values agreed with predicted values to within $\pm 3\%$ over a B_b range of 0–30 mT. The MRI fringe field at the proposed location of the x-ray tube mounted on the C-arm (≈ 4 mT) reduced f_{anode} by only 1%, so x-ray tube heat loadability will not be compromised when using CBXMR systems for percutaneous aortic valve replacement procedures. Eddy current heating power in the rotor due to an MRI fringe field was found to be two orders of magnitude weaker than the heating power produced on the anode due to a fluoroscopic exposure, so eddy current heating had no effect on x-ray tube heat loadability. © 2008 American Association of Physicists in Medicine. [DOI: [10.1118/1.2968337](https://doi.org/10.1118/1.2968337)]

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I. INTRODUCTION

Aortic stenosis is the most common acquired heart valve condition in the Western world.¹ Without treatment, patients have a 2-year mortality rate of 50% once they become symptomatic.² Currently, the only clinically acceptable treatment for this disease is open heart surgical replacement of the aortic valve,³ which provides good clinical outcome for patients.⁴ Unfortunately, one-third to two-thirds of patients who need this treatment do not actually receive it due to risks associated with the surgery.^{4,5}

To increase treatment availability, cardiologists are developing a minimally invasive procedure known as percutaneous aortic valve replacement.^{6,7} This technique replaces the aortic valve of the patient using a minimally invasive catheter-based approach, which is less traumatic for patients than open heart surgery, potentially resulting in greater acceptance of the procedure for patients at high risk for surgery. In order to perform this procedure, a prosthetic valve attached to the end of a catheter is placed into the aortic root with the help of a guidewire. The approach can be via a

femoral artery,⁸ femoral vein,⁹ or the apex of the heart,^{10,11} and after the catheter is placed correctly in the aortic root, the prosthetic valve is permanently anchored in the aortic annulus by balloon inflation.

Percutaneous aortic valve replacement is currently guided using x-ray fluoroscopy and x-ray angiography, which provide high-quality images of catheters, guidewires, the prosthetic valve, the coronary arteries, and the aorta in real time and without motion artifacts.¹² Unfortunately, no soft tissue anatomy of the heart can be visualized in fluoroscopic images, so complications such as cardiac tamponade from tissue perforation have occurred due to the difficulty of positioning and deploying the prosthetic valve.¹³ Thus, the technique is still limited and has only been attempted as a last resort on a small number of patients worldwide.⁹ A better imaging system is therefore needed to increase the frequency and improve the quality of the treatment.

Hybrid x-ray/MRI (XMR) systems combine an x-ray imaging system with an MRI scanner into a single imaging system to provide complementary information for improved

FIG. 1. Closed-bore XMR (CBXMR) system for percutaneous aortic valve replacement. A C-arm x-ray system with a rotating-anode x-ray tube and a flat-panel detector is placed ≈ 1 m from the entrance of a 1.5 T clinical MRI scanner.

clinical benefit.^{12,14–22} MRI can provide the anatomical information that is lacking in the x-ray images. We believe that a new hybrid x-ray/MRI (XMR) system design known as a *closed bore XMR* (CBXMR) (Ref. 23) system will improve the safety and efficacy of percutaneous aortic valve replacement. Figure 1 is a diagram of the proposed CBXMR system. In this system, an x-ray C-arm will be placed close to (~ 1 m) the entrance of a clinical 1.5 T MRI scanner. The patient can be transferred quickly and smoothly between each modality. The short distance between the two modalities will minimize the risk to the patient by eliminating the need to transfer the equipment connected to the patient over long distances. Since undocking the patient table from (or redocking it to) the MRI scanner is not required with the CBXMR system, sudden jarring motions to the patient during patient transfer are abolished.

A number of technical challenges are involved in the construction of the CBXMR system.²³ These include: (1) limiting magnetic field inhomogeneity of the MRI scanner and hence MR image degradation due to the presence of the x-ray C-arm and (2) limiting degradation of the x-ray images in the MRI fringe field by: (a) x-ray tube focal spot defocusing and deflection; (b) flat-panel detector performance degradation; and (c) induction motor performance degradation due to anode rotation frequency reduction and eddy current heating. Preliminary work has shown that magnetic field homogeneity is not affected by the presence of the x-ray system components in the MRI fringe field.²³ The clinical impact of focal spot deflection and defocusing will be investigated in future work, along with proposed solutions to correct these effects.²⁴ It was shown that the performance of an appropriately modified flat-panel detector was also unaffected by the fringe field.¹²

Therefore, this article will investigate the effect of induction motor performance on x-ray tube heat loadability, which has not yet been studied. If anode rotation frequency decreases and eddy current heating in the rotor increases as a

result of the x-ray tube induction motor being in a magnetic field, this will limit the heat loadability of the x-ray tube. A reduced anode rotation frequency would limit the x-ray tube current per exposure that could be used safely for angiography, since the maximum permissible power dissipated on the anode track by the focal spot would be reduced to avoid damaging the anode. This will reduce image quality. Additional eddy current heating in the rotor would increase the heat burden in the anode and the tube housing, limiting the number of allowable exposures for the procedure.

Techniques are developed to measure the effects of reduced anode rotation frequency on anode track heat loadability and eddy current heating on anode/housing heat loadability. Models are also developed to establish the principles of anode rotation frequency reduction and eddy current heating in magnetic fields. The models can be used to predict these effects for an arbitrary rotating-anode x-ray tube if the tube parameters are known. The magnetic field produced by the x-ray tube induction motor (the stator field) and the externally applied magnetic field (the braking field) are required for these models, so these fields are measured. Although these fields vary around the rotor, techniques are developed to obtain single *effective* field values from the field measurements. The effective field values are required for the anode rotation frequency and eddy current heating models. The models are compared with experimental results for the x-ray tubes used in this article in order to test and validate the models for more general applications.

II. PRINCIPLE OF X-RAY TUBE MOTOR OPERATION

Due to the poor x-ray generation efficiency of bremsstrahlung in the anode of the x-ray tube and the medical requirement of an intense source of x-rays from a small focal spot on the anode, a considerable amount of power (up to ≈ 100 kW) is deposited to the anode during an exposure, which generates heat at the small ($\approx 1 \times 5$ mm) focal spot. During the exposure, the anode is rotated at a frequency close to 60 Hz by an induction motor. Rotating the anode enables heat generated at the focal spot to be dissipated more effectively over an annular track instead of a single point in the anode. The rotation thus prevents damage to the anode and permits large tube currents to be used so that sufficient x-ray photons can be generated to produce high-quality images.²⁵ The images are of high quality because producing more photons enables high signal-to-noise ratio images to be produced over short exposure times, which is critical for typical cineangiography needed in percutaneous aortic valve replacement procedures.

There are two key components of the x-ray tube induction motor: the stator and rotor. The stator consists of two pairs of coils embedded in a laminated iron ring. The coils generate a magnetic field and the ferromagnetic ring concentrates it. An ac is passed through both coil pairs in such a way that the second coil pair is phase shifted with respect to the first by 90° , causing the magnetic field to rotate. From 60 Hz ac current excitation, the magnetic field rotates at 60 Hz. Axi-

FIG. 2. The copper cylinder rotor of an x-ray tube induction motor spinning relative to a magnetic field $\vec{B}$. The changing magnetic field induces eddy current loops and magnetic dipole moments $\vec{\mu}$ in the copper cylinder and exerts a torque on it, causing the rotor to rotate in the direction of $\vec{B}$. Because a self-inductance is present in the copper cylinder, $\vec{\mu}$ lags behind $\vec{B}$.

ally centered in the stator is the rotor, which is a freely pivoted copper cylinder on which the x-ray tube anode is mounted.

Figure 2 shows the direction of the rotating stator field relative to the x-ray tube rotor axis of rotation. With the rotor initially at rest, changing magnetic flux from the stator passes through the conducting copper cylinder and generates eddy currents within it. These eddy currents set up magnetic dipole moments $\vec{\mu}$ that are lagging with respect to the stator field $\vec{B}$ due to the self-inductance (which causes phase lag) of the copper cylinder. This lag depends upon how fast the rotor is spinning relative to $\vec{B}$.²⁶ $\vec{B}$ will exert a torque on $\vec{\mu}$ which by Lenz's law will pull the rotor around in the direction of the rotating field (the eddy current loops attempt to resist the change in flux passing through them by following $\vec{B}$). This is the mechanism of torque generation which rotates the anode and accelerates it to a rotational equilibrium, corresponding to a constant angular velocity. In an ideal, frictionless system in rotational equilibrium, the copper cylinder would rotate at the same frequency as $\vec{B}$ and no changing magnetic flux would be detected by the copper cylinder, so no eddy currents (thus no torque) would be generated. However, in a real system, torque is required to maintain anode rotation to overcome energy losses due to friction and eddy current heating. Therefore, at rotational equilibrium, the motor will always have some *slip*, s , where anode rotation frequency will be less than the frequency of the rotating stator field (the synchronous frequency). s at rotational equilibrium is defined as²⁶

$$s = \frac{f_{sy} - f_{anode}}{f_{sy}}, \quad (1)$$

where f_{sy} is the synchronous frequency (60 Hz) and f_{anode} is the rotation frequency of the anode. s will have a value between 0 (where the anode is rotating at f_{sy}) and 1 (where the anode is clamped so it cannot rotate in the laboratory frame of reference and is *stalled*).

If the spinning rotor is brought into a *static* magnetic field perpendicular to its axis of rotation, then the static magnetic

TABLE I. General rotor parameters.

Symbol	Property	Value
σ	Electrical conductivity of copper	$5.9 \times 10^7 \Omega^{-1} \text{ m}^{-1}$
ρ_{Cu}	Density of copper	8920 kg m^{-3}
ρ_{st}	Density of steel	7900 kg m^{-3}
c_{Cu}	Specific heat capacity of copper	$385 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$
c_{st}	Specific heat capacity of steel	$470 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$

field will be rotating relative to the frame of reference of the rotor. Eddy currents will be generated in the same way as for the rotating stator field, except that the static magnetic field will generate a torque to *oppose* anode rotation and thus act as a rotor brake. At rotational equilibrium, the torque delivered by the stator to the anode (the motor torque) will balance the torques produced by friction and the braking field.

III. MODELS

Sections III A and III B provide models to determine the *effective* stator ($B_{s,\text{eff}}$) and braking ($B_{b,\text{eff}}$) magnetic fields acting on the x-ray tube rotor, respectively, using the measured fields around the rotor. Section III C provides a model to predict f_{anode} under rotational equilibrium conditions with $B_{b,\text{eff}}$ applied perpendicular to the anode axis of rotation. Section III D provides a model to predict eddy current heating in the rotor from $B_{s,\text{eff}}$ and $B_{b,\text{eff}}$. All rotor parameters are defined in Tables I and II.

III.A. Effective stator field model

Outside the stator ring and along the axis of rotation for the rotor, the stator field gets weaker farther from the ferromagnetic ring. Since the rotor is longer than the stator ring, the stator field acting on the portion of the rotor not contained within the ring gets weaker towards the ends of the rotor; see Fig. 3(a). This stator field gradient along the rotation axis was approximately linear [see Fig. 3(b) and Sec. VI A]. Therefore, the average field acting on the portion of the rotor outside the stator ring along the rotation axis can be obtained by averaging the following two end points: the field inside the stator ring and the field at either rotor end (≈ 0 mT). This average is simply half of the stator field amplitude inside the ring. $B_{s,\text{eff}}$ is then given by

$$B_{s,\text{eff}} = B_{0r} \left(\frac{d'}{2h} \right) + \left(\frac{B_{0r}}{2} \right) \left(\frac{2h - d'}{2h} \right), \quad (2)$$

where d' is the portion of the rotor length inside the stator ring and $2h$ is the rotor length (see Table II). In this article, B_0 will refer to the stator field amplitude and B_{0r} is the stator field amplitude inside the stator ring. The first term in Eq. (2) is the stator field acting on the portion of the rotor inside the stator ring, and the second term is the stator field acting on the portion of the rotor outside the ring.

TABLE II. Specific rotor parameters.

Symbol	Property	Value for demountable x-ray tube rotor	Value for isolated rotor
h	$\frac{1}{2}$ of the rotor length	40 ± 0.25 mm	43 ± 0.25 mm
r_{out}	Outer radius of the copper cylinder of the rotor	17 ± 0.5 mm	19 ± 0.5 mm
r_{in}	Inner radius of the copper cylinder of the rotor	15 ± 0.5 mm	17 ± 0.5 mm
t_{sl}	Steel sleeve thickness	n/a	1.0 ± 0.5 mm
m_{Cu}	Mass of the copper cylinder of the rotor	140 ± 50 g	170 ± 61 g
m_{sl}	Mass of the steel sleeve	n/a	70 ± 50 g
d'	Stator ring length	35 ± 0.5 mm	35 ± 0.5 mm
$f(\lambda, \mu)$	Electric potential function	0.30	0.23

III.B. Effective braking field model

The stator ring shields the center of the rotor from braking fields arising from an external static magnetic flux by providing a low reluctance path for the magnetic flux to bypass the rotor. Therefore, a reduced braking field acts on the part of the rotor inside the stator ring. Outside the stator ring along the rotation axis, the braking field at the rotor increases from the ring boundary to each rotor end; see Fig. 3(c). Figure 3(d) shows the linear gradient for the braking field, described in Sec. VI B.

$B_{b,\text{eff}}$ is obtained by averaging braking field components along the length of the rotor. Therefore, $B_{b,\text{eff}}$ acting on the rotor is given by

$$B_{b,\text{eff}} = \frac{B_{b,\text{inC}} + B_{b,\text{inF}}}{2} \left(\frac{d'}{2h} \right) + \left(\frac{B_{b,\text{endC}} + B_{b,\text{ringC}}}{2} + \frac{B_{b,\text{endF}} + B_{b,\text{ringF}}}{2} \right) \times \left(\frac{2h - d'}{2h} \right) \quad (3)$$

where $B_{b,\text{inC}}$ and $B_{b,\text{inF}}$ are the measured braking fields at the center of the stator ring, at the outer rotor surfaces closest to (location C) and farthest from (location F) the MRI scanner, respectively [see Fig. 3(e)]. C and F are along the entire rotor length. $B_{b,\text{endC}}$ and $B_{b,\text{endF}}$ are the measured braking fields at

the rotor end closest to the anode at C and F, respectively. $B_{b,\text{ringC}}$ and $B_{b,\text{ringF}}$ are the measured braking fields at the stator ring boundary [see Fig. 3(c)] closest to the anode at C and F, respectively. The first term in Eq. (3) is the braking field acting on the segment of the rotor contained within the stator ring, using the average of $B_{b,\text{inC}}$ and $B_{b,\text{inF}}$ as the braking field. The second term is the braking field acting on the segment of the rotor not contained within the ring. In this term, the braking field is taken as the average of the fields acting along C and F outside of the ring. Averages of the fields are taken with two data points because of the approximately linear field gradients. B_b will refer to the applied braking field with no ferromagnetic components being present.

III.C. Anode rotation frequency model

f_{anode} at rotational equilibrium can be estimated in the following manner. At rotational equilibrium, the motor torque must have equivalent magnitude to the sum of the magnetic braking torque and the torque due to friction.

Schafer and Heiden have derived a model for the torque acting on a conducting cylinder rotating in magnetic fields perpendicular to the rotation axis.^{27,28} They showed that the electric potential produced in the cylinder by the magnetic field is a solution to Laplace's equation, since the electric fields of the eddy currents in the rotor are confined to loops and have no divergence. Using cylindrical boundary conditions, the electrical potential and therefore the electric field produced in the cylinder can be determined. From this result, the torque acting on the conducting copper cylinder rotor can be determined.

Before $B_{b,\text{eff}}$ is applied, $B_{s,\text{eff}}$ must overcome the torque produced by friction. At rotational equilibrium, the torque produced by friction is equal to the motor torque provided by $B_{s,\text{eff}}$. Therefore, the torque due to friction is given by²⁷

$$\tau_f = 2\pi^2 \sigma s f_{\text{sy}} B_{s,\text{eff}}^2 r_{\text{out}}^5 f(\lambda, \mu), \quad (4)$$

where $s f_{\text{sy}}$ is the frequency at which $B_{s,\text{eff}}$ rotates with respect to the rotor, where s_f is the slip due to friction. $f(\lambda, \mu)$ is an electric potential function²⁷ that depends on the geometry of the copper cylinder, where $\lambda = r_{\text{in}}/r_{\text{out}}$ and $\mu = h/r_{\text{out}}$ (see Table II for definitions).

For a given f_{sy} , s_f and τ_f are constant and are unaffected by changes in rotor angular velocity caused by $B_{b,\text{eff}}$. This is because τ_f depends only upon the coefficient of friction of the bearings in the rotor, the normal force of the anode on the bearings, and the radius of the rotor. None of these quantities is affected by the angular velocity of the rotor.

If $B_{b,\text{eff}}$ is now applied to the rotor, the motor torque must overcome the torque due to friction and due to magnetic braking at rotational equilibrium. The motor torque in this case is given by

$$\tau_m = \tau_f + \tau_b, \quad (5)$$

where τ_b is the torque due to magnetic field braking. The motor torque at rotational equilibrium is given as²⁷

FIG. 3. (a) Top view of the rotor and stator showing the B_0 gradient from stator ring boundaries to the ends of the rotor. B_0 decreased from the ring boundaries to ≈ 0 mT at either rotor end. (b) B_0 gradient measurements at the outer rotor surface. The solid line is a least-squares linear fit to the data. (c) Top view of the rotor and stator showing the braking field gradient from the stator ring boundaries to the rotor ends. (d) Gradient of the braking field from $B_{b,ringC}$ to $B_{b,endC}$ at the outer rotor surface closest to the MRI scanner with an applied braking field of $B_b = 20$ mT. The solid line is a least-squares linear fit to the data and error bars are smaller than the markers on the plot. (e) Outer surfaces of the rotor where $B_{b,eff}$ measurements were taken. Locations C and F are the outer rotor surfaces closest to and farthest away from the MRI scanner entrance, respectively, along the entire rotor length.

$$\tau_m = 2\pi^2 \sigma s f_{sy} B_{s,eff}^2 r_{out}^5 f(\lambda, \mu), \quad (6)$$

where s is the slip caused by both friction and magnetic field braking. $s f_{sy}$ is the rotation frequency of $B_{s,eff}$ relative to the rotor, with magnetic braking included. τ_b is given by²⁷

$$\tau_b = 2\pi^2 \sigma (1-s) f_{sy} B_{b,eff}^2 r_{out}^5 f(\lambda, \mu), \quad (7)$$

with $(1-s)f_{sy}$ being the rotation frequency of the rotor with respect to $B_{b,eff}$ at rotational equilibrium. Equations (4), (6), and (7) can be substituted into Eq. (5) to solve for s , yielding

$$s = \left(\frac{B_{b,eff}^2 + s_f B_{s,eff}^2}{B_{s,eff}^2 + B_{b,eff}^2} \right). \quad (8)$$

s_f would need to be measured without any B_b applied. Using Eq. (1), f_{anode} in $B_{b,eff}$ is then given by

$$f_{anode} = (1-s) f_{sy}. \quad (9)$$

III.D. Eddy current heating model

The electromotive forces produced in the rotor by magnetic fields depend on the strength of the magnetic fields and

how fast the fields are rotating with respect to the rotor. This would imply that the power delivered to the rotor by eddy currents as a result of these electromotive forces depends on the angular velocity of the rotor and the torques being applied to it by the magnetic fields. The electric fields in the eddy current loops are nonconservative, since the path integral of the electric field around any loop (or work done by the field per unit charge) is nonzero according to Faraday's law. Therefore, the energy delivered to the rotor by the electric fields in the eddy current loops must be in the form of heat.

The power, P , dissipated in the rotor as heat is given by²⁷

$$P = \tau_m \omega_m + \tau_b \omega_b. \quad (10)$$

In Eq. (10), $\omega_m = 2\pi s f_{sy}$ and $\omega_b = 2\pi(1-s)f_{sy}$. τ_m and τ_b are obtained from Eqs. (6) and (7), respectively. The first and second terms in Eq. (10) are the powers dissipated in the rotor by B_{s_eff} and B_{b_eff} , respectively.

IV. MATERIALS

Section IV A describes the x-ray tubes used in our experiments. Section IV B describes the magnets used in our experiments. An electromagnet and a non-self-shielded MRI scanner were used to measure anode rotation frequency of the x-ray tubes in magnetic fields. A self-shielded MRI scanner was used to determine the braking fields around the x-ray tube induction motor in a clinical setting. Section IV C describes the microphone used to pick up the sound made by the rotating anode and from this measure anode rotation frequency.

IV.A. X-ray tubes

The first x-ray tube used in our experiments was a standard radiography tube (Duratron PX-1461ES, Dunlee Inc., Aurora, IL), which was used to assess the performance of an induction motor of a typical rotating-anode x-ray tube in B_b . For comparison with the f_{anode} model, a second x-ray tube known as the demountable x-ray tube was also used (model DX 69B, Machlett Laboratories Inc., Springdale, CT), composed of an x-ray tube glass insert and an iron ring stator. The rotors of both x-ray tubes contained steel sleeves to enhance magnetic coupling of B_{s_eff} to the rotor. These steel sleeves were concentric with and inside the copper cylinders. In the demountable x-ray tube, the steel sleeve was not clamped to the frame of the rotor and did not rotate with it. For comparison with the eddy current heating model, an isolated rotor/stator assembly was used. This assembly was constructed by centering an *isolated* rotor (extracted from an x-ray tube insert) inside a stator ring and clamping it in place with plastic foam.

IV.B. Magnets

A large diameter (≈ 30 cm) air-cored electromagnet (Stangenes Industries, Palo Alto, CA) was designed so that the standard radiography x-ray tube could be placed in a uniform B_b such that f_{anode} could be measured with a micro-

FIG. 4. X-ray tube placed inside an air-cored electromagnet such that the magnetic field is perpendicular to the anode axis of rotation. The x-ray tube was centered within the coil pair. The center point, D, of the electromagnet is located at the center of the spacing between its two coils. $\vec{z}$ is the direction along the center axis of the electromagnet, as the MRI scanner convention. The $\vec{y}$ direction is in the vertical direction. The $\vec{x}$ direction is in the horizontal direction in a plane parallel to the coil faces.

phone at a bench top. Figure 4 shows the electromagnet setup such that B_b was perpendicular to the axis of rotation of the rotor. The directions, $\vec{x}$, $\vec{y}$, and $\vec{z}$, used to define B_b produced by the electromagnet are shown. The center point D between the two coils is also shown. Figure 5 shows the electromagnet used with B_b parallel to the axis of rotation.

The electromagnet consisted of a pair of coils mounted on an aluminum frame. The windings were made with both copper wire and aluminum wire (diameter: #7 AWG) to optimize the weight and the heat dissipation capability of the system. A 9 in. gap separated the coils. At a coil current of 14 A, the electromagnet generated $B_b = 23$ mT at D along its center axis. The electromagnet current was supplied by a 1 kW dc power supply (Interfax Systems, Toronto, ON, Canada), which reached a maximum voltage of 60 V during operation.

The electromagnet was calibrated to determine how B_b was related to the coil current. B_b along $\vec{z}$ ($B_{b,z}$) was measured with a Hall effect sensor probe system (model 4048, F.W. Bell, Orlando, FL) at D of the electromagnet for a range

FIG. 5. X-ray tube placed inside the air-cored electromagnet such that the magnetic field is parallel to the axis of rotation.

FIG. 6. Electromagnet field uniformity. $B_{b,z}$ was measured over a range of distances in $\vec{x}$, $\vec{y}$, and $\vec{z}$, as defined in Fig. 4. The coil current was set to 7 A and the origin $(x,y,z)=(0,0,0)$ point was the center point, D, shown in Fig. 4. (a), (b), and (c) show the uniformity of $B_{b,z}$ in $\vec{x}$, $\vec{y}$, and $\vec{z}$, respectively. Error bars are smaller than the markers on the plot.

of coil current. B_b generated by the electromagnet was linear with respect to the current in the coils, with a calibration factor of 1.6 mT/A at its center.

Field uniformity of the electromagnet was also measured, to determine the variation of $B_{b,z}$ in the region of the induction motor of the x-ray tube. $B_{b,z}$ was measured over a range of distances ($> \pm 10$ cm) in $\vec{x}$, $\vec{y}$, and $\vec{z}$ around D (see Fig. 4). The coil current was set to 7 A.

Figure 6 shows the uniformity of $B_{b,z}$ of the electromagnet. The uniformity of $B_{b,z}$ is shown over $\vec{x}$, $\vec{y}$, and $\vec{z}$, respectively, around D. In Fig. 6, D was located at $(x,y,z)=(0,0,0)$. $B_{b,z}$ was not uniform in any direction, but the uniformity of $B_{b,z}$ over the volume occupied by the induction motor when placed at D was within $\pm 5\%$ of $B_{b,z}$ at D, assuming the motor occupied a cubic volume with sides of ≈ 12 cm. Therefore, $B_{b,z}$ can be approximated to be uniform in the volume of the electromagnet where the x-ray tube motor is to be positioned.

f_{anode} of the demountable x-ray tube was measured in B_b of a non-self-shielded 1.5 T MRI scanner (General Electric Signa 1.5 T). The fringe field of this scanner was strong far

FIG. 7. f_{anode} of the demountable x-ray tube measured with a microphone. No B_b was applied. The large peaks below 60 Hz are the f_{anode} values. (a) f_{anode} measured immediately after the motor was disconnected from the power supply. (b) f_{anode} measured 30 s after the motor was disconnected from the power supply. Sixty Hz interference from surrounding electrical equipment is also present in the plot.

from the scanner entrance, and changes in f_{anode} could be visualized directly in the demountable x-ray tube.

A self-shielded 1.5 MRI scanner (General Electric Signa Excite 14.0) was used to measure the components of $B_{b,\text{eff}}$ around the x-ray tube induction motor since this type of scanner would be used in a clinical situation.

IV.C. Microphone

Figure 7 is an example of the Fourier transform signal from the microphone when used on the demountable x-ray tube with $B_b=0$ mT. The motor was turned on and the anode was brought to rotational equilibrium. The motor was then turned off and f_{anode} was measured. Figure 7 shows the microphone signal (a) immediately after the motor was turned off and (b) 30 s later. A frequency peak below 60 Hz corresponded to f_{anode} . A peak at 60 Hz was also present. This was interference present in the laboratory environment from 60 Hz power.

V. METHODS

Section V A describes a technique for measuring the ac stator field using a detection coil. Section V B describes a method for measuring the dc braking field using a Hall effect sensor. Section V C describes two techniques to measure anode rotation frequency at rotational equilibrium, and Sec. V D describes an experiment to measure power dissipated in a rotor due to eddy current heating.

FIG. 8. (a) Experimental apparatus for the measurement of the stator field around the circumference of the rotor. A detection coil was placed around the rotor circumference to obtain rms values for B_0 and B_{0r} . Electromotive forces were produced in the detection coil by the stator field and measured with an oscilloscope, from which the stator field amplitude could be determined. (b) Experiment for measurement of power dissipated in an isolated rotor from eddy currents generated by $B_{s,eff}$ using a digital thermometer (thermocouple) and the isolated rotor/stator assembly. The temperature was measured on the inner steel sleeve and the copper cylinder rotor. The rotor was clamped inside the stator for all measurements using plastic foam.

V.A. Stator field measurement

Figure 8 shows a set of experiments performed with the rotor of the isolated rotor/stator assembly [see Sec. V D for the details of Fig. 8(b)]. Figure 8(a) shows the apparatus to measure B_0 (and B_{0r}) of the demountable x-ray tube and the isolated rotor/stator assembly. A detection coil wound from magnet wire was introduced into the gap between the iron stator ring and the rotor. The detection coil had $N=8$ turns and a mean diameter of $D=2.65 \pm 0.1$ cm. When the stator was excited, the resulting B_{0r} induced a sinusoidal electromotive force (emf) in the stationary coil by Faraday's law, and was measured using an oscilloscope. ε_{pk} is the peak value of the sinusoidal waveform produced. From ε_{pk} , B_{0r} is given by

$$B_{0r} = \frac{2\varepsilon_{pk}}{\pi^2 D^2 N f_{sy}}. \quad (11)$$

B_{0r} was measured around the circumference of the rotor to obtain a root-mean square (rms) value for B_{0r} . The rms value of B_{0r} was used for the models of Sec. III since f_{anode} and P depend on the square of the field strength. This technique was also used to measure B_0 and its gradient along the length of the rotor. B_{0r} was substituted into Eq. (2) to determine $B_{s,eff}$.

V.B. Braking field measurement

$B_{b,eff}$ was determined using the apparatus of Fig. 9(a). The isolated rotor/stator assembly was mounted to the patient cradle of the self-shielded 1.5 T MRI scanner using an alu-

FIG. 9. (a) Measurement of the braking field acting on an isolated rotor using the isolated rotor/stator assembly in the fringe field of a self-shielded 1.5 T MRI scanner. A Hall effect sensor probe system was placed on the outer rotor surface. The components of $B_{b,eff}$ and B_b parallel to the center axis of the MRI scanner ("on-axis" B_b) were measured. Field curvature was determined by measuring "off-axis" B_b , 40 cm away horizontally from the center MRI axis. The isolated rotor/stator assembly was brought into MRI fringe fields of increasing strength, in increments of 10 mT. (b) Experiment for measuring f_{anode} of the demountable x-ray tube with B_b perpendicular to the axis of rotation. The demountable x-ray tube was placed in an aluminum mount and fastened to the patient cradle of the non-self-shielded MRI scanner and the demountable x-ray tube was brought into MRI fields of increasing strength. At each field strength, f_{anode} was measured directly with a strobe light.

minum mounting assembly along the center axis of the MRI scanner. The axis of rotation of the rotor was set perpendicular to the center axis of the MRI scanner. "On-axis" B_b is defined as the component of B_b parallel to the center axis of the MRI scanner. The dependence of the $B_{b,eff}$ components [Eq. (3)] on on-axis B_b was measured, since on-axis B_b is perpendicular to the axis of rotation. These fields were measured using the Hall effect sensor probe system at the rotor as the isolated rotor/stator assembly was brought closer to the MRI scanner entrance in steps.

Adjacent to the isolated rotor/stator assembly (≈ 40 cm away horizontally from the MRI central axis), B_b was no longer parallel to the MRI center axis ("off-axis" B_b). The angle, α , of off-axis B_b with respect to the axis of rotation was measured at all the assembly positions used in Fig. 9(a). These measurements were required to determine the effect of B_b curvature on the magnetic shielding performance of the stator ring for the rotor. The components of off-axis B_b parallel and perpendicular to the MRI central axis were measured with the Hall effect sensor probe system, from which α could be determined.

To investigate the degree of saturation in the stator ring by B_b , the isolated rotor/stator assembly was placed in the electromagnet such that $B_b=23$ mT was perpendicular to the anode rotation axis. The current through the stator coils was

FIG. 10. Experimental apparatus to measure f_{anode} of the standard radiography x-ray tube, with B_b applied (a) parallel and (b) perpendicular to the anode axis of rotation. The x-ray tube was centered in an air-cored electromagnet and f_{anode} was measured with a microphone placed on the x-ray tube housing above the stator ring. The microphone signal was sent to a computer and Fourier transformed to determine f_{anode} . A and C refer to the anode and cathode sides of the x-ray tube, respectively.

measured using an oscilloscope and B_{0r} was measured using the detection coil, with and without B_b applied. These measurements were extended to stronger B_b by applying a 200 mT permanent magnet to the stator ring in place of the electromagnet.

V.C. Anode rotation frequency measurement

Figure 9(b) shows an apparatus used to measure equilibrium f_{anode} of the demountable x-ray tube. The demountable x-ray tube was mounted to the patient cradle of the non-self-shielded MRI scanner. The motor was subjected to gradually increased MRI fringe fields in steps. At each step, f_{anode} was measured with a Strobotac Type 1531 strobe light (GenRad, Concord, MA).²³

Once the air-cored electromagnet became available, the remainder of the f_{anode} measurements were taken with it. The electromagnet was much more convenient for measuring f_{anode} than the MRI scanner since all measurements could be performed in a laboratory environment with computer processing. Equilibrium f_{anode} measurements were obtained for the standard radiography tube in the electromagnet with a microphone using the arrangement shown in Fig. 10 for B_b generated by the air-cored electromagnet (a) parallel and (b) perpendicular to the anode rotation axis. The microphone was mounted just above the stator ring on the tube housing for both configurations. The signal from the microphone was sent to a computer and Fourier transformed to elucidate f_{anode} . This approach enabled f_{anode} to be measured without direct visualization of the anode, so no removal of the x-ray tube insert from its housing was required.

V.D. Eddy current heating measurement in the rotor

Figure 8(b) shows an apparatus used to measure the power dissipated by eddy currents in the rotor using the isolated rotor/stator assembly. The rotor was stalled such that the maximum amount of heat could be produced by the stator field for effective temperature measurements. A stalled, isolated rotor provided good access and secure positioning for temperature measurement. The stator was powered on and $B_{s,\text{eff}}$ rotating at 60 Hz was generated that caused eddy current heating in the stalled rotor. An HH81 digital thermometer (Omega Engineering Inc., Stamford, CT) was used to measure the change in rotor temperature as a function of time, using a type K (Chromel/Alumel) thermocouple sensor. The thermometer was mounted to the outer surface of the rotor (copper) centered inside the stator ring and a thermal compound (Wakefield Engineering Inc., Pelham, NH) was used to establish thermal equilibrium between the rotor and the thermometer.

The sequence of operations was to first cool the rotor, turn the stator on, and then measure the temperature over 30 s. The short timeframe for temperature measurements ensured that the heat was confined to the copper cylinder rotor and its steel sleeve, without being conducted to the rotor shaft or anode, or radiated to the surrounding air.

The power dissipated in the copper cylinder and steel sleeve is given by

$$P_m = (m_{\text{Cu}}\Delta T_{\text{Cu}}c_{\text{Cu}} + m_{\text{sl}}\Delta T_{\text{s}}c_{\text{sl}})/S, \quad (12)$$

where the specific heat capacities and masses of the copper cylinder and steel sleeve are given in Tables I and II, respectively. ΔT_{Cu} and ΔT_{s} are the temperature changes of the copper cylinder and steel sleeve, respectively. S is the 30 s measurement time.

The temperature measurements were taken for the steel sleeve by mounting the thermometer on the inside surface of the steel sleeve. To measure the amount of heat from the external environment contributing to the temperature rise of the rotor, temperature measurements after cooling of the copper cylinder and steel sleeve were taken over 30 s without applying eddy currents. These results were used to correct for the heating due to the eddy currents only.

VI. RESULTS

Sections VI A and VI B describe the stator field and braking field results, respectively. Section VI C shows f_{anode} measurements. Section VI D provides the rotor temperature change and eddy current heating results. Error analysis was performed using the error propagation equation.²⁹

VI.A. Stator field measurement

Table III summarizes the stator field measurements. The range between the minimum and maximum B_{0r} was ≈ 24 mT around the rotor circumference, or $\approx 50\%$ of the rms B_{0r} . Therefore, a significant variation of the stator field amplitude was present around the rotor circumference.

TABLE III. Stator field measurements.

Apparatus	B_{0r}	$B_{s,eff}$
Demountable x-ray tube	52.5 ± 1.9 mT	37.7 ± 1.4 mT
Isolated rotor/stator assembly	45.5 ± 2.1 mT	32.0 ± 1.5 mT

As expected, B_0 decreased from the stator ring to the end of the rotor along the rotation axis. This is shown in Fig. 3(b), where the B_0 gradient along the rotation axis is approximately linear, with B_0 dropping to 0 mT at the end of the rotor.

VI.B. Braking field measurement

Figures 11(a) and 11(b) show plots of the $B_{b,eff}$ field components [Eq. (3)]. Figure 11(c) is a plot of $B_{b,inC}/B_{b,endC}$ as a

FIG. 11. (a) Plot of $B_{b,inC}$, $B_{b,ringC}$, and $B_{b,endC}$ vs B_b . The circles are the experimental data. The solid line is a linear least-squares fit to the $B_{b,endC}$ data. The dotted and dashed curves are quartic least-squares fits to $B_{b,inC}$ and $B_{b,ringC}$, respectively. (b) Plots of $B_{b,inF}$, $B_{b,ringF}$, and $B_{b,endF}$. $B_{b,endF}$ was fitted linearly and $B_{b,ringF}$ and $B_{b,inF}$ were fitted quartically. (c) Plot of $B_{b,inC}/B_{b,endC}$ over the angle of B_b relative to the anode rotation axis, α . Error bars are smaller than the markers on the plots.

FIG. 12. f_{anode} measurements of both x-ray tubes at rotational equilibrium over a range of B_b applied perpendicular to the anode axis of rotation. The solid curve (from Sec. III C) shows the predicted f_{anode} curve for the demountable x-ray tube. The dashed curve shows the experimental f_{anode} results for the standard radiography x-ray tube. Most of the error bars are smaller than the markers on the plot.

function of α (see Sec. V B). α decreased as the isolated rotor/stator assembly was brought closer to the MRI scanner entrance. At $\alpha > 60^\circ$, $B_{b,inC}/B_{b,endC}$ was low but increased substantially for $\alpha < 60^\circ$. At $\alpha = 48^\circ$, $B_{b,inC}/B_{b,endC}$ approached unity. Figure 3(d) shows the gradient of $B_{b,ringC}$ to $B_{b,endC}$ along the surface C of the rotor for $B_b = 20$ mT. The gradient was approximately linear.

B_{0r} and the current entering the stator coils were unaffected by B_b being applied perpendicular to the anode rotation axis when the isolated rotor/stator assembly was placed in the electromagnet. The permanent magnet caused no change in stator coil current or B_{0r} .

VI.C. Anode rotation frequency measurement

Figure 12 shows the results of the f_{anode} measurements. The demountable x-ray tube f_{anode} decreased by 8.4% over the field strength range of the MRI fringe field. f_{anode} of the standard radiography tube decreased by 5.7% over the field strength range of the electromagnet. No change in f_{anode} exceeding ± 0.2 Hz was detectable for the demountable x-ray tube or the standard radiography tube when placed in B_b parallel to the anode rotation axis.

VI.D. Eddy current heating measurement in the rotor

Figure 13 is a plot of rotor temperature change over time from $B_{s,eff}$ producing eddy currents in the isolated rotor. The temperature of the copper cylinder and the steel sleeve increased over the 30 s measurement time. Using Eq. (12), $P_m = 14 \text{ W} \pm 3.0 \text{ W}$.

Without applying eddy currents, the temperature of the copper cylinder and steel sleeve after cooling did not fluctuate by more than $\pm 0.1^\circ \text{C}$ over a 30 s time period. No increase in temperature was observed, so no correction for heating from the environment was needed.

VII. DISCUSSION

Section VII A explains the stator field. In Sec. VII B, the braking field measurements are discussed. Section VII C

FIG. 13. Measurements of rotor temperature over time to determine eddy current power dissipation in the rotor due to $B_{s,eff}$. The solid and the dashed lines were fitted to the temperature change of the outer copper cylinder surface and inner steel sleeve surface, respectively.

compares measured anode rotation frequency results with the model of Sec. III C. In addition, the impact of reduced anode rotation frequency on x-ray tube anode track heat loadability is discussed. Section VII D compares the measured eddy current heating with the model of Sec. III D. The model is also used to predict rotor heating from the stator and braking fields over a range of anode rotation frequencies. This section also discusses the effect of rotor heating on the anode/housing heat loadability of x-ray tubes.

VII.A. The stator field

In Sec. VI A, a difference in electrical resistance (and hence electric current) between each stator coil pair caused the variation of B_{0r} around the rotor, since B_{0r} is proportional to the stator coil current. Although a uniform value of B_{0r} around the rotor would simplify the model for $B_{s,eff}$, obtaining an rms value for B_{0r} was effective for addressing the field variation for the model.

The stator field gradient was more gradual than the gradient expected from a pure magnetic dipole moment, for which the field drops inversely with the cube of the distance from the dipole. This was because the ferromagnetic steel sleeve in the rotor confined B_0 tightly through the rotor. Also, the stator coils were of comparable size to the length of the rotor, so higher order terms for the magnetic dipole field of the coils became more significant.

VII.B. The braking field

The stator ring was very effective at shielding the rotor from low B_b . At stronger B_b , the shielding provided by the stator ring was less effective. The stator ring is composed of electrical steel (iron embedded with silicon), which is a soft ferromagnetic material. Soft ferromagnetic materials have a high relative magnetic permeability, making them excellent magnetic shields.³⁰ Electrical steel is able to shield up to $B_b \approx 1.7$ T, at which point it saturates. B_b of the MRI scanner never exceeded this field, and experimental results show that the stator ring did not reach saturation. At saturation, the inductance of the stator coils would decrease, since magnetic permeability would be reduced. However, the inductance is

FIG. 14. Proposed solution for improving the performance of an x-ray tube induction motor in B_b , such as the fringe field of an MRI scanner. (a) The standard configuration of an induction motor of a rotating-anode x-ray tube. The iron stator ring contains a small center portion of the rotor. (b) A possible solution for designing an x-ray tube induction motor to be used in stronger B_b . The stator ring is longer and thicker to reduce the magnetic reluctance and provide improved magnetic shielding over the entire length of the rotor.

equal to the flux of B_{0r} through the stator coils divided by the stator coil current. From the results of Sec. VI B, neither of these quantities changed in B_b , so saturation did not occur. Soft ferromagnetic materials also have a low coercive force, so they magnetize quickly in the direction of the rapidly changing stator field and have a low hysteresis energy loss, which is necessary for effective motor operation. Therefore, electrical steel is an ideal material for both stator performance and magnetic shielding.

The reduced shielding at low α in Fig. 11(c) is due to the increased curvature of B_b as the isolated rotor/stator assembly is brought closer to the MRI scanner entrance. At low B_b far from the scanner entrance, B_b was nearly perpendicular to the anode rotation axis, so very little magnetic flux was able to enter the air gap between the stator and the rotor. Therefore, minimal flux was present in the stator/rotor air gap to be diverted through the rotor by the stator, resulting in effective magnetic shielding. Closer to the scanner entrance, the component of B_b parallel to the rotation axis (which is perpendicular to the MRI center axis) is more pronounced. This is because the MRI scanner is a superconducting solenoid and the fringe field curvature off of the center axis of a solenoid is more pronounced near its ends than farther away from its ends (the MRI scanner entrance is one end of a solenoid). Near the MRI scanner entrance, a strong magnetic flux is able to enter the stator/rotor air gap and be diverted through the rotor in a perpendicular direction to the rotation axis by the stator from the inside of the gap, resulting in less effective shielding. This agrees with the results of Fig. 11.

The results of Sec. VI B have implications for improving x-ray tube motor performance and tube heat loadability in B_b . A stator ring could be designed to be thicker, longer, and of smaller mean radius to reduce its magnetic reluctance³¹ for B_b and to improve shielding of the rotor; see Fig. 14. For percutaneous aortic valve replacement, however, this modification will not be required, since a negligible decrease in f_{anode} occurs with the x-ray tube placed ≈ 1 m out from the MRI scanner entrance (see Sec. VII C). It would only be required in applications where the x-ray tube is exposed to strong B_b .

VII.C. Anode rotation frequency impact on anode track heat loadability

The f_{anode} model in Fig. 12 agreed with experimental f_{anode} results to within $\pm 3\%$ for the demountable x-ray tube. No change in f_{anode} was observed with B_b parallel to the anode rotation axis because the low magnetic reluctance stator ring diverted B_b towards the ring symmetrically around the rotor circumference. In this case, B_b directed along the anode rotation axis was uniform (Fig. 6), unlike the fringe field of the MRI scanner. Therefore, no net magnetic flux from B_b acted on the rotor.

Three kinds of heating are present in an x-ray tube: anode track heating, heating of the entire anode, and heating of the tube housing. A reduced f_{anode} as a result of placing an x-ray tube in B_b reduces its anode track heating limit for a single exposure. The maximum permissible power that can be dissipated at the focal spot on the anode for a single exposure is $\propto \sqrt{f_{\text{anode}}}$.³² The effect of reduced f_{anode} on maximum permitted track heating requires the angiographic charts of the x-ray tube being used. These charts describe the maximum power per exposure that can be dissipated in the track of the anode given the frame rate, the time for each exposure, and the number of exposures in the cine run, enabling the kVp and tube current to be set appropriately.³³ The adjusted maximum power limit P_A in B_b is given by

$$P_A = P_O \sqrt{\frac{f_{\text{anode},A}}{f_{\text{anode},O}}}, \quad (13)$$

where P_O is the original track heating power limit in $B_b = 0$ mT, $f_{\text{anode},O}$ is the anode rotation frequency in $B_b = 0$ mT, and $f_{\text{anode},A}$ is the anode rotation frequency in B_b .

For percutaneous aortic valve replacement, however, the x-ray tube will be placed ≈ 1 m from the MRI scanner entrance and ≈ 50 cm under the patient table. This location for the x-ray tube under the table will provide a source-to-image distance of ≈ 1 m, which is typically required for interventional cardiology procedures. At this location, B_b perpendicular to the anode rotation axis was measured to be ≈ 4 mT at the self-shielded 1.5 T MRI scanner with the Hall effect sensor probe system. This would reduce f_{anode} and maximum permitted anode track heating by $\approx 1\%$ (see Fig. 12), which would have a negligible adverse impact on clinical performance. This fringe field strength would not be exceeded even with oblique angulation of the C-arm. Therefore, the x-ray tube induction motor will not require any modifications.

Note that focal spot deflection in a magnetic field can also affect anode track heating, since the maximum permissible power dissipation on the track is proportional to the square root of the mean track diameter.³² The track diameter changes with the deflection, so this deflection must be corrected in an x-ray tube.

VII.D. Eddy current heating impact on anode/housing heat loadability

In Sec. V D, the rotor in the isolated rotor/stator assembly was stalled ($s=1$) and $B_b=0$ mT. Substituting these values into Eq. (10) yields a predicted dissipated power of P

FIG. 15. (a) Predicted eddy current power dissipation in the isolated rotor due to $B_{s,\text{eff}}$ and $B_{b,\text{eff}}$ over the full range of equilibrium f_{anode} . (b) Predicted power dissipation in the isolated rotor as a function of $B_{b,\text{eff}}$. In (a) and (b), the solid curve, dashed curve, and dotted curve predict the total, $B_{s,\text{eff}}$, and $B_{b,\text{eff}}$ dissipated power in the rotor, respectively.

$= 15.4 \pm 1.5$ W. This value agrees with the experimental value of $P_m = 14.0 \pm 3$ W to 10%. Since a negligible temperature increase in the rotor was observed over a 30 s period after it was cooled without eddy currents being applied, P was caused by eddy current heating exclusively and there was no contribution to P from the external environment around the rotor.

The inner steel sleeve boosted $B_{s,\text{eff}}$ and improved magnetic coupling through the rotor, but since the electrical resistivity of steel is an order of magnitude larger than the resistivity of copper, it was assumed that the dominant source of eddy currents was the copper cylinder exclusively. The eddy current heating power generated in the copper cylinder was rapidly transferred to the steel sleeve to which it was connected.

The heating model of Eq. (10) can be used to predict eddy current heating when the rotor is placed in B_b perpendicular to the axis of rotation over all s (from $s=0$ to 1). Figures 15(a) and 15(b) show the predicted heating. In Fig. 15(a), P is shown as a function of f_{anode} . Implicit in Fig. 15(a) is $B_{b,\text{eff}}$ that causes the rotor to spin at the f_{anode} values shown. P is shown as a function of $B_{b,\text{eff}}$ in Fig. 15(b).

At typical anode rotation frequencies (57 Hz) with $B_b \approx 4$ mT, $B_{b,\text{eff}}$ contributes ≈ 2 times more P than $B_{s,\text{eff}}$. However, the rotor heating even at high B_b will not contribute significantly to the total x-ray tube heat loading since the maximum P dissipated in the rotor is ≈ 3.5 W in Fig. 15(a). This can be compared to ≈ 200 W power dissipation for continuous fluoroscopy. Thus, rotor heating is not a significant clinical concern because of its low power dissipation com-

pared to a fluoroscopic exposure. At very low f_{anode} values, eddy current heating due to B_b decreases since the anode is rotating slowly. The strongest eddy current heating (≈ 15 W) occurred when the rotor was stalled, with no contribution to heating from B_b . Even at stall, eddy current heating power was an order of magnitude weaker than the power dissipation from fluoroscopy.

VIII. CONCLUSIONS

A model was developed and verified by experiment to predict f_{anode} reduction in an MRI magnetic fringe field. A technique was also described to predict the corresponding reduction in anode track heat loadability as a result of the decrease in f_{anode} . Another model was developed and experimentally verified to predict eddy current heating in the rotor due to the fringe field. This model was able to predict fringe field heating in the rotor over the entire range of f_{anode} . These models can be used to predict heat loadability for an arbitrary rotating-anode x-ray tube in any MRI fringe field for CBXMR systems.

We have established that the clinical requirements for percutaneous aortic valve replacement of adequate room for the clinical team to work at the MRI scanner entrance and no sudden jarring motions to the patient will be met if the x-ray C-arm is placed ≈ 1 m from the MRI scanner entrance. At this location, the fringe field of the MRI scanner was insufficient to cause any degradation of anode track heat loadability due to f_{anode} reduction. The fringe field also caused insufficient eddy current heating in the rotor to degrade anode/housing heat loadability. Therefore, the x-ray tube induction motor can be placed in this fringe field environment without requiring any modifications. However, if the C-arm needs to be placed closer to the MRI scanner entrance for other applications, heat loadability reduction could be a more serious concern.

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^{a)}Electronic mail: john.bracken@sri.utoronto.ca

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