Radiation induced currents in MRI RF coils: application to linac/MRI integration

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Abstract

The integration of medical linear accelerators (linac) with magnetic resonance imaging (MRI) systems is advancing the current state of image-guided radiotherapy. The MRI in these integrated units will provide real-time, accurate tumor locations for radiotherapy treatment, thus decreasing geometric margins around tumors and reducing normal tissue damage. In the real-time operation of these integrated systems, the radiofrequency (RF) coils of MRI will be irradiated with radiation pulses from the linac. The effect of pulsed radiation on MRI radio frequency (RF) coils is not known and must be studied. The instantaneous radiation induced current (RIC) in two different MRI RF coils were measured and presented. The frequency spectra of the induced currents were calculated. Some basic characterization of the RIC was also done: isolation of the RF coil component responsible for RIC, dependence of RIC on dose rate, and effect of wax buildup placed on coil on RIC. Both the time and frequency characteristics of the RIC were seen to vary with the MRI RF coil used. The copper windings of the RF coils were isolated as the main source of RIC. A linear dependence on dose rate was seen. The RIC was decreased with wax buildup, suggesting an electronic disequilibrium as the cause of RIC. This study shows a measurable RIC present in MRI RF coils. This unwanted current could be possibly detrimental to the signal to noise ratio in MRI and produce image artifacts.

1. Introduction

The integration of medical linear accelerators (linac) with magnetic resonance imaging (MRI) systems has recently become an exciting area of research in radiotherapy physics. Two groups are at the forefront of this research into image-guided radiotherapy (IGRT) (Fallone *et al* 2007, Lagendijk *et al* 2005). The MRI in these integrated units will provide real-time tumor tracking during radiotherapy treatment, allowing for improved knowledge of tumor location. In current radiotherapy treatments, the geometric margin around the tumor is added to account for the day-to-day changes in tumor location during the course of fractionated radiotherapy caused by patient setup and internal tumor motion. IGRT uses daily imaging, at the time of treatment, to more accurately locate the tumor in an effort to decrease the added geometric margin around the tumor. Current IGRT techniques use

megavoltage (MV) portal imaging, kilovoltage (kV) radiographic imaging, MV computed tomography (CT), MV cone beam CT, kV cone beam CT and ultrasound (Verellen *et al* 2007, Dawson and Jaffray 2007). However, the current 3D imaging methods that support IGRT suffer from poor soft-tissue contrast, when compared to MRI, and are unable to provide real-time images during the treatment beam-on time; thus significant margins around the tumor are still needed. MRI has exquisite soft tissue contrast, utilizes non-ionizing radiation and can acquire images during the pulsing of the radiation beam; these properties make MRI ideal for its use in IGRT. These units will allow for decreased geometric margins around the tumor resulting in the increased sparing of normal tissues and critical structures from irradiation.

The two research groups mentioned above have very different designs for their integrated systems: our group at the Cross Cancer Institute (Edmonton, Canada) has a prototype that uses a low field, bi-planar magnet integrated with a 6 MV linac (Fallone *et al* 2007), while Lagendijk's group at the University Medical Center Utrecht (Utrecht, The Netherlands) uses a high field, cylindrical magnet integrated with a 6 MV linac (Lagendijk *et al* 2005). Preliminary results from both groups have been published in dosimetry simulation papers (Kirkby *et al* 2008, Raaijmakers *et al* 2008) and more recently both groups have published MRI images taken with prototype units while the linac is producing radiation (Fallone *et al* 2009, Raaijmakers *et al* 2009). During the course of a typical treatment using one of these integrated units, the MRI radio frequency (RF) coils will be exposed to the pulsed radiation beam of the linac causing unwanted radiation induced effects. There are different types of possible radiation induced effects: (a) instantaneous—coincides with linac radiation pulses and includes the radiation induced current, (b) accumulative—occurs over time and could include damage to the RF coil hardware and (c) dosimetric—modification of the patient skin dose caused by the presence of the RF coil in the magnetic field. This work will focus solely on the instantaneous radiation induced effects.

When thin materials, such as the copper strips found in MRI RF coils, are irradiated with high-energy (megavoltage) photons, the high-energy electrons produced in Compton interactions are likely to escape the material. If there is no influx of electrons to balance this effect, a net positive charge is created in the material. If the material is part of an electrical circuit, then a current will begin to flow in order to neutralize this charge imbalance. This current is termed as the radiation induced current (RIC) and has been reported on by several authors. Meyer *et al* (1956) reported in 1956 on the RIC seen in polyethylene and Teflon upon exposure to x-rays from a 2 MeV Van de Graaff generator and a ^{60}Co beam. Johns *et al* (1958) reported the RIC due to the ^{60}Co beam in parallel plate ionization chambers providing RIC as the basis of the polarity effect observed in these chambers. Several authors have published reports on RIC in varying materials when exposed to pulsed radiation (Degenhart and Schlosser 1961, Sato *et al* 2004, Abdel-Rahman *et al* 2006), which are of particular relevance to this work.

Since the premise of linac–MRI integration is based on simultaneous irradiation and MRI data acquisition, and MRI forms an image from the signals induced in RF coils, the RIC induced in the MRI RF coils could be detrimental to the MRI signal to noise ratio and introduce image artifacts. These accurate images are necessary for the success of real-time

image guidance. It is therefore imperative that the RIC in MRI RF coils be investigated. The objective of this work is to report on the measurement of the instantaneous RIC in two different MRI RF coils exposed to linac pulsed radiation, to examine the frequency characteristics of the RIC and to determine some of the fundamental characteristics of the RIC.

2. Materials and methods

2.1. Dependence of the RIC on the RF coil and microwave power source

The experimental setup is shown schematically in figure 1. The RF coil is placed on a wooden stand inside a Faraday type RF cage (Model FC-10, LBA Technologies, Greenville, NC) to shield the RIC measurements from unwanted RF noise produced by the clinical linacs (Burke *et al* 2009). Two different coils were used (figure 2). A CAT solenoid coil (National Research Council Canada) has copper strips as the windings with a resonant frequency at ~8.5 MHz. It has an inner diameter of 9.5 cm, a length of 11.7 cm and five continuous windings of thin, 1.2 cm wide copper sheet. The second coil was a black solenoid coil (National Research Council Canada) of 10.0 cm inner diameter and 12.0 cm length, and it is made of a 0.64 cm diameter hollow copper pipe. Five concentric rings are connected in series to provide a solenoid structure. A capacitor connects each concentric ring to the next. An inductive matching network (a copper ring with an 820 pF capacitor) is employed to connect the resonator with an active T/R switch incorporated with the coil. The tuning range for the black solenoid coil is from 9.2 MHz to 9.4 MHz. These coils were designed for a 0.2 T (CAT) and 0.22 T (black solenoid) magnets, respectively, and both have an impedance of 50 Ω at resonance. The CAT coil is a receive-only coil, while the black solenoid coil is a transmit/receive coil. The coils were connected to a high-speed, low-current amplifier (Model 59–179, Edmund Optics, Germany), with a 50 Ω input impedance, via a coaxial cable. All the measurements were made with a nominal gain setting of 10^5 V A^{-1} and a nominal bandwidth of 10 MHz. The amplifier is not irradiated. The power supply and amplifier output connections are brought to the exterior of the RF cage through RF filters. A coaxial cable from the exterior of the RF cage connects the amplifier output to an oscilloscope (Model DSO6104A, Agilent Technologies, Santa Clara, CA) which measures the induced current. The RF cage is then placed on the treatment couch of the linac and exposed to pulsed radiation to induce current in the RF coil. The center of the coil is placed at approximately 115 cm from the radiation source and the field size was chosen to cover the entire coil. Two different linacs were used: a Varian 600C and a Varian Clinac 23iX (Varian Medical Systems, Palo Alto, CA), being powered by a magnetron microwave source and a klystron microwave source, respectively. A nominal 6 MV x-ray beam was used for irradiation in all experiments with an approximate dose of 0.04 cGy/pulse at 100 cm from the source. The signal voltage waveforms, sampled at 2 GHz and triggered using the magnetron/klystron current (available as a test signal at the linac console), are transferred from the oscilloscope to a PC using a Keithley KUSB 488 GPIB interface (Keithley Instruments Inc., Cleveland, OH) implemented with the software program DADiSP (DSP Development Corporation, Newton, MA). The 2 GHz sampling frequency is the oscilloscope default that is not variable. This high sampling rate provides little benefit to the measured

frequency spectrum of RIC since the amplifier bandwidth extends only to 10 MHz. The frequency spectra of the measured signals were then calculated using DADiSP as follows:

$$S(f) = \sqrt{\frac{\sum_{i=1}^N |\text{DFT}_i(s(t))|^2}{N}}, \quad (1)$$

where DFT is the discrete Fourier transform, $s(t)$ is the time-dependent voltage waveform, N is the number of signal acquisitions (1000) and $S(f)$ is the final frequency spectrum. Since the bandwidth selected for the current amplifier at the specified gain setting was 10 MHz, any frequencies above 10 MHz were ignored in the spectral data. The measured frequency response of the current amplifier, $G(f)$, was used to correct the measured power spectrum to obtain appropriate current spectral density values, $I(f)$:

$$I(f) = \frac{S(f)}{G(f)}. \quad (2)$$

Using the methods just described, four different measurement scenarios will be presented using each of the two MRI RF coils exposed to radiation by each of the two linacs.

2.2. Characterization of the RIC

Further experiments were performed to determine some characteristics of the RIC such as isolating the coil component responsible for the RIC, its dependence on the dose rate and the effect of adding buildup material. These three experiments were performed on the CAT coil alone using the same setup as described above. The CAT coil was favored over the black coil because of its continuous coil winding and simpler electronic circuitry. Also the CAT coil has a more uniform RIC curve which makes the interpretation of experimental data simpler.

To isolate the source of the RIC, the coil/cage setup was placed as close to the linac treatment head as possible. A 2.5 cm wide beam, whose length was sufficient to cover the coil diameter, was stepped along the length of the coil. At each step, the RIC was measured. A measurement was also taken with the entire coil in the linac beam for comparison purposes. The linac used for this experiment was the Varian 600C producing a nominal 6 MV x-ray beam. A 10 μ s acquisition window was used to display the oscilloscope traces.

The effect of the dose rate on the RIC was determined by varying the distance between the RF coil and the radiation source. For these RIC measurements, the linac average dose rate (MU min^{-1}) is not the quantity of interest. The dose per pulse of the linac will determine the magnitude of the RIC in the measured pulses. The dose per pulse can easily be varied by varying the distance of the coil from the source. The distance was incremented by 5 cm steps from an initial source-to-coil distance of 67.5 cm to a final source-to-coil distance of 107.5 cm. At each distance the radiation beam covered the entire coil. Once acquired, an average signal was obtained at each distance by taking the mean of the uniform portion of the RIC curves, and this was then plotted against the inverse square of the source-to-coil distance. The linac used for the experiment was the Varian 600C, using a nominal 6 MV x-ray beam.

Finally, the effect of wax buildup on the RIC was examined by placing the coil in the linac beam without any buildup and then with wax buildup placed outside and inside the coil (figure 3). This experiment was performed on a Varian Clinac 23iX in a nominal 6 MV x-ray beam.

3. Results

3.1. Dependence of the RIC on the RF coil and microwave power source

The measured RIC curves are displayed in figures 4 and 5. The displayed RIC curves are time averaged for display purposes only, while the individual acquisitions were used in the spectral analysis described in section 2. All figures have an identical x -axis span of $20 \mu\text{s}$, but the y -axes have been adjusted for display. Figure 4 shows the measured RIC for the CAT and black solenoid coils, when exposed to the pulsed radiation of the Varian 600C, magnetron-powered linac. There are clear differences between the RIC pulse shapes in the two coils. The CAT coil displays an RIC curve that is approximately the duration of the magnetron current pulse and the linac radiation pulse ($\sim 5 \mu\text{s}$). The black solenoid coil shows a more gradual increase and decrease in RIC, its duration is longer than that of the linac radiation pulse ($\sim 10 \mu\text{s}$), measured from the first appearance of the signal ($\sim 6 \mu\text{s}$) until the signal returns to 0 ($\sim 16 \mu\text{s}$). Figure 5 shows the RIC curves for the CAT and black solenoid coils, measured when exposed to the pulsed radiation of the Varian 23iX, klystron-powered linac. Again the CAT coil shows a RIC curve whose pulse length is approximately the same as the linac radiation pulse, while the black solenoid coil again shows a RIC curve which is very different from that of the CAT coil. The RIC of the black solenoid coil measured on the klystron unit (figure 5) is consistent in shape with the RIC curve measured on the magnetron unit (figure 4).

The results of the spectral analysis described in section 2 are shown in figures 6 and 7. Figures 6 and 7 are the root-mean-squared (RMS) spectral densities corresponding to the cases shown in figures 4 and 5, respectively. All of these figures are displayed from 0 to 10 MHz and plotted on a vertical log scale with the same range to allow for direct comparison.

Inspection of the figures shows that all four scenarios have a maximum RIC component around dc. As expected, there are significant differences between the RIC spectra of the CAT and the black solenoid coils. Figure 6 shows that the CAT coil has an oscillating decrease in RIC from dc to approximately 4 MHz and then has a steady increase from approximately 4 MHz to 7.5 MHz, followed by a sudden drop to a minimum near the coil resonant frequency. Figure 6 also shows that the black solenoid coil has a dissimilar response; it decreases steadily, aside from a small increase around 6.5 MHz, from dc until it has a maximum around the coil resonant frequency of 9.3 MHz. Figure 7 shows a similar oscillating decrease from dc to 4 MHz in the CAT coil, but the oscillations extend all the way out to 6.5 MHz in this case. Figure 7 also shows that the increase that occurs at 4 MHz is much smaller in span compared to that in figure 6, but again there is a minimum around the coil resonant frequency. Finally, figure 7 shows that the black solenoid coil again has a very steady decrease in RIC from dc all the way out to the maximum near the coil resonant frequency.

3.2. Characterization of RIC

The results of the experiments described in section 2.2 are shown in figures 8–10. Figure 8 shows clear evidence that the major source of the RIC is the copper windings of the RF coil. When the small beam is focused on part of the copper winding, a much smaller current is induced compared to when the entire coil is irradiated. Also, when the beam is not incident on the copper windings there is a small negative current induced, likely caused by some small scatter from the aluminum RF cage.

Figure 9 shows the effect of the dose rate on the RIC. The average current was calculated as the mean of the uniform portion of the RIC curves. Figure 9 shows a steady decrease in RIC as the separation is incrementally increased. Note that the reference distance in the figure represents the largest separation distance, 107.5 cm, mentioned in section 2.2, so moving to the right on the x -axis represents moving the coil closer to the radiation source. Figure 9 shows a very linear relationship between the inverse squared distance and the average induced current.

The addition of wax buildup to the CAT coil had the effect of reducing the magnitude of the RIC (figure 10). It is important to note that although the magnitude of the RIC was decreased, it was not eliminated.

4. Discussion

Examining the results presented in figures 4 through 7 there is a definite, measurable RIC present when MRI RF coils are exposed to the pulsed radiation of a linac. The presence of this effect is independent of the coil used, evident from the presence of RIC in both coils. It is also independent of the microwave power source of the linac, whether magnetron or klystron, evident from RIC measured on both linacs.

However, the time-based characteristics (i.e. RIC signal shape) are not independent of these factors. There is a very obvious difference between the RIC in the CAT and the black solenoid coils (figures 4 and 5). The RIC in the CAT coil is very similar in duration to the magnetron (figure 4) and klystron (figure 5) current pulses, while the RIC in the black solenoid coil has a very distinct shape and duration, which does not correspond to the magnetron and klystron current pulses. A plausible cause for the different shapes of the RIC curves may be the difference in electronic circuitry present in the two coils. The CAT coil is a receive-only coil with simple matching and tuning circuitry, while the black solenoid coil is a transmit/receive (T/R) coil and as such has a more complicated circuitry. Certain circuit elements could be more radiation sensitive than others. The T/R switch circuit in the black solenoid coil could be modifying the shape of the RIC. This hypothesis can be tested by removing the transmit/receive switch circuit from the coil. This was not done as the coil was borrowed and could not be dismantled. The black coil also has capacitors in between each coil winding (as stated above) and these could be storing charge or simply modifying the shape of the RIC, thus causing the shape seen in figures 4 and 5.

There are also some small, qualitative differences seen between the RIC generated by the magnetron-powered and the klystron-powered linacs. The largest difference seen (figures 4

and 5) when comparing these curves is that the klystron linac RIC pulse has faster rise and fall times compared to the magnetron linac. The cause of these differences is likely the differences in function between the magnetron and klystron: the magnetron is an oscillator with a slower rise and fall of microwave pulses and some signal oscillation, while the klystron is merely an amplifier and so does not suffer these effects (Karzmark *et al* 1993). The effects of these linac-based differences are likely insignificant as the RIC is still present in both cases and needs to be addressed regardless of its shape.

Next, the frequency characteristics of the RIC were examined as shown in figures 6 and 7. As expected, based on the initial shapes of the RIC curves, there are qualitative differences seen between the spectra seen for the CAT and the black solenoid coils that were mentioned in section 3. A. Again, these differences could be caused by the circuitry of the coils and there is some evidence in these figures that supports this hypothesis. Namely, there are distinct features in the spectra for both coils near their resonant frequencies. The CAT coil shows a decrease in signal near 8.5 MHz in the spectra from both linacs, while the black solenoid coil shows an increase in signal near its resonant frequency of 9.3 MHz for both linacs (figures 6 and 7). The reason for the opposite trends in the two coils is not known at this time.

It would have been interesting to speculate on the impact of RIC on the received signals in MRI. However, the MRI signal is highly variable and depends upon several factors including the Larmor frequency, applied B1 field strength and the available magnetization in the sample. Moreover, the amount of voltage presented by the RIC to the input of pre-amplifier in the signal acquisition chain depends upon the frequency spectrum of the RIC and the frequency-dependent input impedance of the pre-amplifier.

It should also be noted that the frequency analysis was performed to examine the frequencies present in the RIC for our specific experiments. Theoretically, only the signals around the Larmor frequency (42.6 MHz T^{-1} for hydrogen) are important in MRI. However, the experimental signal acquisition chain is complex involving pre-amplification, variable gain amplification, analog and digital filtering, heterodyne mixing and digitization. Therefore, the impact of the RIC on the images will depend upon both the magnetic field strength and the particular configuration of the data acquisition chain. Moreover, the magnitude and spectrum of the RIC is also dependent upon the dose rate of the radiation producing device. Thus, it is easier to explore the effect of the RIC on the SNR in MR images experimentally which is the topic of future investigation.

Finally, some experiments were performed to characterize the RIC, as described in section 2.2, and the results were briefly described in section 3.2. These results indicated that the copper winding of the RF coil is the main source of RIC, the RIC is linearly dependent on dose rate and the RIC is diminished, but not eliminated, with the application of wax buildup. These results suggested that the probable mechanism for this current is an electronic disequilibrium in the copper windings of the RF coils. If the electronic equilibrium could be established within the RF coil windings without detriment to the coil's function, then it is possible that the RIC could be eliminated. This could be achieved by placing copper as the buildup and backscattering material in the coil, insulated from the coil winding. Further

investigation of the RIC and electronic equilibrium are being carried out in flat copper strips using measurements and Monte Carlo simulation. Using Monte Carlo simulation, the difference in the net charge entering and leaving a scoring region, i.e. a flat copper strips or a circular winding of real coil, is calculated which is related to the radiation induced current (Abdel-Rahman *et al* 2006).

5. Conclusions and future work

The results show that although the specific characteristics of RIC may change with the type of MRI RF coil and the type of linac, the effect is still present and needs to be investigated and eliminated. The copper windings of the coil were isolated as the main source of RIC. A linear dependence of RIC on the dose rate was seen. Wax buildup decreased the magnitude of the measured RIC, but did not eliminate it. The authors hypothesize that the RIC seen in MRI RF coils is due to an electronic disequilibrium in the copper windings of the coil and that RIC may be eliminated if equilibrium could be established.

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Figure 1. Schematic representation of the RF coil inside a Faraday cage (dotted line). The pulsed radiation beam is focused on the RF coil. The radiation induced current is amplified and then detected by a digital oscilloscope, which is triggered by the linac magnetron/klystron current.

Figure 2.
CAT solenoid coil (left) and black solenoid coil (right). The strips of copper winding can be seen in the bore of the CAT coil, while the black coil has more cylindrical copper windings.

Figure 3.
CAT coil with wax buildup applied.

Figure 4.
Time averaged oscilloscope trace of CAT coil RIC measured on a Varian 600C linac.

Figure 5.
Time averaged oscilloscope trace of CAT coil RIC measured on a Varian Clinac 23iX.

Figure 6. Frequency spectrum of CAT and black solenoid coils RIC measured on a Varian 600C linac, calculated as the RMS magnitude of the DFT.

Figure 7.

Frequency spectrum of CAT and black solenoid coils RIC measured on a Varian Clinac 23iX, calculated as the RMS magnitude of the DFT.

Figure 8.

Isolation of copper winding as the source of radiation induced current. Magnitude of the RIC pulse is larger when the entire coil length is irradiated compared to only 2.5 cm width. A very small current of opposite polarity occurs when the copper winding is not directly irradiated.

Figure 9.

Mean current from uniform portion of RIC traces at various distances from the source plotted against the inverse squared distance. The error bars on the data points are of the same size as the plotted dots. D_0 is the reference distance and D is the distance between the coil and radiation source.

Figure 10.

Effect of wax buildup on radiation induced current. The magnitude of the RIC pulse is reduced due to the build up indicating electronic disequilibrium as the possible mechanism of RIC.