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Do induction cooktops interfere with cardiac pacemakers?

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Aims In induction cooktops, coils produce time-varying magnetic fields that induce eddy currents in the ferromagnetic bottom of a pot or pan, thereby heating it, while the cooktop itself remains cool. Interference with pacemaker sensing could conceivably be produced by voltages induced directly by induction or indirectly by leakage currents.
Methods and results A worst-case pacemaker-patient (PP) model representing left-sided implantation of a unipolar pacemaker was used for measurement of induced voltages, to judge whether induction cooktops could interfere with pacemaker sensing. Eleven induction cooktops of European manufacture were tested using the PP model. The pacemaker sensitivity with respect to 24 kHz voltages, amplitude-modulated at 100 Hz, was investigated in 244 devices. The current passing through the body of a grounded patient touching a metal pot was determined by measuring the voltage from hand to hand and between electrodes placed on the thorax to simulate an implanted unipolar pacing system underneath. The results obtained were complex. If the pot is positioned concentrically with the induction coil, the smallest pot produced the largest stray field, but the induced voltage always remained below the critical value of 100 mV. With eccentrically positioned large pots, voltages of up to 800 mV could be induced. The induced voltage could always be reduced to ≤60 mV by maintaining a distance of 35 cm. The most sensitive pacemaker reacted at 90.5 mV. Because of leakage current, ∼2% of the voltage between pot and ground appears across the pacemaker's sensing input.
Conclusion Patients are at risk if the implant is unipolar and left-sided, if they stand as close as possible to the induction cooktop, and if the pot is not concentric with the induction coil. Unipolar pacing systems can sense interference generated by leakage currents if the patient touches the pot for a long period of time. The most likely response to interference is switching to an asynchronous interference mode. Patients with unipolar pacemakers are at risk only if they are not pacemaker-dependent.

Introduction

An electric cooking stove normally consists of an oven with a roasting or grilling element and a cooktop that produces heat for cooking in any of several ways: thermal heating of spiral wires, production of infrared light, or electrical induction. Induction cooktops produce magnetic fields that generate heat in ferromagnetic cooking vessels, causing eddy currents within the bottom of a pot or pan. Induction cooking is used increasingly in professional kitchens and private households because of its advantages: higher efficiency, faster cooking, and better control of heating. Induction cooktops are designed to turn off the field if the pot is removed or placed eccentrically relative to the centre of the induction coil.

The possibility of interference sensing by pacing systems from induction cooktops has been investigated in *in vitro* and *in vivo* studies.[1,2] The results of these studies are controversial: the *in vitro* study showed interference, but in the *in vivo* study, no evidence whatever of interference was found. Both studies, however, suffered from limited numbers of pacemakers and induction-cooktop models.

Since 1995, the first author has repeatedly been asked by manufacturers of induction cooktops to investigate whether sensing interference could be generated by induction cooktops and whether such interference could be potentially harmful to a patient. The results of his investigations indicate that only patients with unipolar pectoral implants are at potential risk and suggest that patients who are not pacemaker-dependent may be at slightly greater risk due to competition between their underlying rhythm and the temporary asynchronous pacing provided by a pulse generator that recognizes the presence of electromagnetic

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interference. How such patients could avoid interference of an induction cooktop, if it exists at all, and how modern pacemakers react in the presence of voltages typical of such cooktops will be outlined in detail below.

Pacemaker interference: theoretical background

Theory of heat induction

If a current I passes through a straight conductor, it creates a magnetic field $\boldsymbol{H}$ concentric with the conductor, whose strength decreases with the perpendicular distance r from the conductor. If the conductor is formed into a coil with n windings, the magnetic field is reinforced n-fold. Thus, the magnetic field within and outside the coil is a function of I, n, and r. In vector notation,

$$\boldsymbol{H} = \boldsymbol{H}(I, n, r). \tag{1}$$

The strength of the magnetic field $\boldsymbol{H}$ is measured in Amperes per metre (A/m). The effect of induction depends upon the magnetic flux density $\boldsymbol{B}$, also called induction, which is proportional to the magnetic field. The constant of proportionality is the magnetic permeability μ:

$$\boldsymbol{B} = \mu \boldsymbol{H}. \tag{2}$$

The permeability has two components, μ_0, the permeability of free space, and μ_r, the relative permeability, and is the scalar product of both:

$$\mu = \mu_r \mu_0 \tag{3}$$

The permeability of free space is

$$\mu_0 = 4\pi \times 10^{-7} (\mathrm{T/A/m}), \tag{4}$$

where the units are the Tesla ($\mathrm{T} = \mathrm{V\,s/m^2}$) divided by Amperes per metre.

The relative permeability μ_r is unity for all diamagnetic and paramagnetic materials, but is much greater in ferromagnetic materials such as iron or nickel. In ferromagnetic nickel–iron alloys, μ_r can be as high as 20 000. Thus, ferromagnetic materials can convert a magnetic field $\boldsymbol{H}$ to a strong induction $\boldsymbol{B}$ and simultaneously concentrate all field lines within the material.

According to Maxwell's law (James Clerk Maxwell, 1831–79), an electric field E is induced in a circular conductor like the bottom of a pot according to the relationship

$$E(r) = \frac{r}{2} \bullet \frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}. \tag{5}$$

Because of the large μ_r of the ferromagnetic bottom, the induced electric field is also very strong, causing eddy currents in the bottom of the pot, which, in turn, produce a magnetic field opposite to that of the cooktop's induction coil. The two fields tend to cancel each other out, so that there is almost no stray field if the induction coil is completely covered by the pot. Thus, magnetic fields capable of generating pacemaker interference are only to be expected if the pot is smaller than the coil or if the pot is positioned eccentrically. If the power provided by the cooktop is decreased by geometric eccentricity (and the reactive power is increased in consequence), the cooktop can detect the absence or eccentric placement of the pot. Thus, a non-ferromagnetic, excessively small, or ill-positioned pot is recognized and the power is turned off automatically. All induction cooktops we investigated possessed this eccentricity-detection feature and switched off when appropriate, if the real power was below a critical value, a safety measure which is absent in gas cooktops and present only in rare thermal-heating electric cooktops equipped with a switch in the centre of each heating element.

Theory of voltage induction

From Faraday's law (Michael Faraday, 1791–1867), the time derivative $\mathrm{d}\boldsymbol{B}/\mathrm{d}t$ of the induction induces a voltage in a planar area $\boldsymbol{A}$ given by:

$$U_{\mathrm{ind}} = \boldsymbol{A} \bullet \frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}, \tag{6}$$

if $\boldsymbol{B}$ is constant within the area $\boldsymbol{A}$ and perpendicular to the plane of $\boldsymbol{A}$. Otherwise, the product of $\mathrm{d}\boldsymbol{B}/\mathrm{d}t$ and $\boldsymbol{A}$ must be calculated by integration. U_{ind} represents the induced voltage. We will use the symbol U for the voltage instead of V throughout the text to avoid confusion of the symbol with its unit of measurement (V). Because $\boldsymbol{A}$ and $\boldsymbol{B}$ are vectors (values with spatial direction), Eq. (6) is only valid for the component of $\boldsymbol{B}$ perpendicular to the plane of $\boldsymbol{A}$. An angle other than zero between the two reduces the induced voltage U_{ind}. Field lines of $\boldsymbol{B}$ must, therefore, permeate the area $\boldsymbol{A}$ to induce a voltage.

Calculation of the voltage U_{ind} induced by a time-varying induction $\boldsymbol{B}$ is mathematically very demanding and, in some instances, impossible. It is advantageous, therefore, to develop a model with which such voltages can be measured experimentally. We proposed such a model that is described elsewhere.[3] It takes into account the fact that a left-sided pacemaker system implanted with a 60 cm lead forms a nearly semicircular area of 200 $\mathrm{cm^2}$ to which the remaining, coiled area of the lead (24.6 $\mathrm{cm^2}$) must be added. This model, called a pacemaker-patient (PP) model, is depicted in *Figure 1*. The model simulates a large patient with a left-sided unipolar pacing system and thus represents the worst case with respect to magnetic induction. A right-sided unipolar pacemaker system forms a smaller area as is demonstrated in *Figure 2*.

If an induction-cooktop coil produces a magnetic field, it is easy to determine which position of the PP model experiences the largest voltages. The PP model must be perpendicular to the plane of the coil, in closest possible proximity, and with the edge of the model at the level of the coil (*Figure 3A*). If the PP model is positioned symmetrically with respect to the coil plane (*Figure 3B*), the induced voltage is zero, because all magnetic field lines entering the area above the coil plane emerge below it. One can also infer from *Figure 3A* that the elevation of the PP model above the coil plane reduces the induced voltage less than it would if the PP model was displaced horizontally, because as the distance from the centre of the coil increases, the field lines become increasingly vertical.

Theory of leakage currents

If two conducting planes are positioned in close proximity, as the plane of the coil faces that of the pot bottom, they form an electrical capacitor, a circuit element capable of storing electric charge. If a voltage is applied to the coil, the pot bottom becomes charged by capacitance. A time-varying voltage with a given frequency will alter the charge on this capacitor periodically, causing a leakage current to

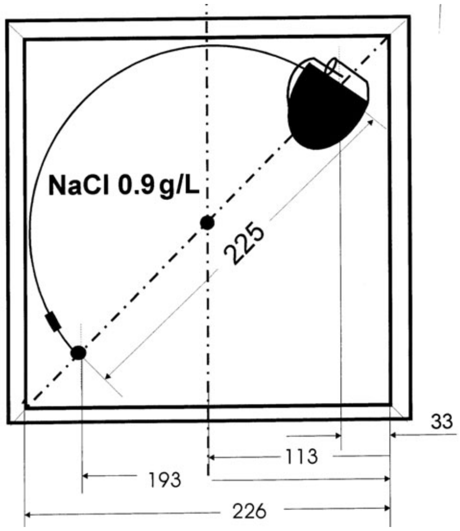

Figure 1 Sketch of an artificial PP model for investigating magnetic field influence. The model simulates an implanted pacemaker system with a semi-circular area of 200 cm^2. The superfluous 24.6 cm of a 60 cm lead is coiled twice behind the pulse-generator housing, forming an additional area of 25 cm^2, so that the total area which may be exposed to magnetic fields is 225 cm^2. The PP model is especially useful in investigating inhomogeneous magnetic fields. The thickness of the chamber is 33 mm. All dimensions shown are in millimetres.

flow if the pot is touched by a grounded person (for instance, one stirring with a metal spoon and simultaneously touching a grounded part of the cooktop). A capacitance on the order of 100 pF to which a 25 kHz voltage is applied has a source impedance of ~60 kΩ, which characterizes a current source. The leakage current, therefore, is nearly independent of the load of the person in contact with the pot, so that the higher the body impedance, the higher the voltage produced across the thorax. A deeper view into theory reveals that this is only true for the fundamental frequency (the first harmonic) of the induced voltage. If the voltage is not sinusoidal but is distorted by the presence of higher harmonics, the impedances for the higher harmonics are lower. They decrease to 20 kΩ for the third harmonic, to 12 kΩ for the fifth, and to 8.6 kΩ for the seventh, still aggravating the distortion.

The body surface represents a large plane in proximity to the grounded environment (all metallic parts of the oven, and all water installations, grounded lamps, or household appliances with grounded metal surfaces), so that a person is also capacitively coupled to ground. The capacitance of an adult is of the order of 150 pF, which is in series with that of the coil-bottom capacitor described above. The impedance of two capacitors in series is always smaller than that of a single capacitor, so higher source impedance with reduced current is to be expected.

Reaction of pacemakers to interference

If the amplitude of continuous interference is above the frequency-dependent interference threshold, all pacemakers react by switching to their 'interference' or 'noise' mode, which is asynchronous pacing at a rate determined by the adaptive-rate system, if present, or the programmed lower-rate limit if rate modulation is absent. The (non-programmable) interference mode in DDD or DDDR pacing is DOO or VOO, according to manufacturer's design.

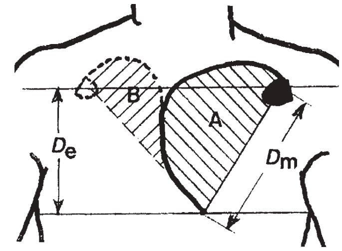

Figure 2 Sketch of a unipolar pacemaker system in pectoral position either on right or left side. For magnetic fields, the area formed by the lead is decisive: it is nearly a semi-circular area ***A*** with the diameter D_m on the left side and smaller area ***B*** when positioned on the right side. Distance D_e is effective for electric fields.

Methods

Investigation of induction cooktops

The PP model illustrated in *Figure 1* was placed as close as possible to the induction cooktop, as shown in *Figure 2A*. The site of maximum voltage was located by vertical and horizontal movement of the PP model. This position simulates a person standing with the thorax pressed against the edge of the stove. This geometry must be regarded as excessively pessimistic, because an adult's pacemaker system is normally higher. Starting from this worst-case position, the PP model was moved vertically and horizontally, and the voltages in several positions were measured as functions of distance, pot size, and eccentricity.

The voltage of the PP model was measured with a differential amplifier with variable (mostly 10-fold) gain, input resistance 1 MΩ, and low-pass filtering at 125 kHz, connected to a 'signal computer' with display (i.e. a digital oscilloscope). Signals could be stored in 46 memories for off-line evaluation.

Eleven different induction cooktops of different European manufacturers were investigated.

Investigation of pacemakers

To assess the voltages measured with the PP model described above, sensing thresholds were measured for 244 pulse generators explanted from patients deceased between September 2001 and September 2004. All pulse generators studied were implanted between 1998 and 2003. We chose 24 kHz because we had already performed a similar investigation with 217 explanted pulse generators in 1995.[4] It was felt that repeating the investigation in the same way would allow us to demonstrate the possibly improved interference rejection of more modern pulse generators.

There is a CENELEC standard[5] for interference sensing thresholds expressed as peak-to-peak voltages U_{PP} measured at frequencies f from 3 to 150 kHz, expressed by:

$$U_{pp}/\text{mV} \geq 6f/\text{kHz}. \qquad (7)$$

Inserting 25 kHz for f in Eq. (7) yields six times 25 = 150 mV. Thus, interference sensing threshold should be at least 150 mV for a frequency of 25 kHz according to this standard, which was approved in 2003. An older standard was less stringent, demanding thresholds one-third of those required by Eq. (7).[6]

Investigation of leakage currents

To identify the voltages generated at the sensing input of a unipolar pacemaker system within the thorax created by leakage currents flowing from hand to hand, a group of volunteers was recruited, all of whom supplied written informed consent to participate in the study. It consisted of 12 male and 12 female students from 22 to 30 years of age. Both genders were investigated separately to assess the accuracy of our assertion under Theory of Leakage Currents discussed earlier to the effect that the higher the body impedance, the higher the voltage produced across the thorax.

The method used for voltage measurements is illustrated in *Figure 4*. Two electrocardiographic (ECG) electrodes were placed where a pulse generator might be implanted on the right (position A) and left (position B) sides, below the clavicle. A third ECG electrode was placed just below the apex of the heart (position C). Right- and left-sided unipolar pulse generators within the thorax would see approximately U_{AC} and U_{BC}, respectively. U_{PG} is the voltage between the pot and ground.

The voltages U_{PG} and U_{AC} were measured for each volunteer, and a ratio r was calculated as follows:

$$r = \frac{U_{AC}}{U_{PG}} \quad (8)$$

from which the mean value r_{mean} and standard deviation (SD) for each subgroup (male and female) were calculated. From these values, the maximum ratio r_{max} was estimated according to Eq. (9):

$$r_{max} = r_{mean} + 2\ \mathrm{SD} \quad (9)$$

which represents the worst case for leakage-current production of interference. Knowing r_{max} allows us to estimate the fraction of the voltage that might appear across the input of an implanted pulse generator, if the voltage between the hands is known.

The voltage U_{PG} between the pot and ground and the transthoracic voltage were measured with a two-channel storage oscilloscope with differential inputs (1 MΩ input resistances). By measuring the voltage with a high-impedance (10 MΩ) probe with ten-to-one voltage division and then by loading it with a low resistance (100 Ω), the source impedance of the capacitive system could be determined from the ratio of load-free voltage to short-circuit current.

A second similar group of subjects consisted of 10 male volunteers in whom voltages were compared with the subjects grounded and ungrounded. For each subject, the ratio $R = U_{ungrounded}/U_{grounded}$ was calculated.

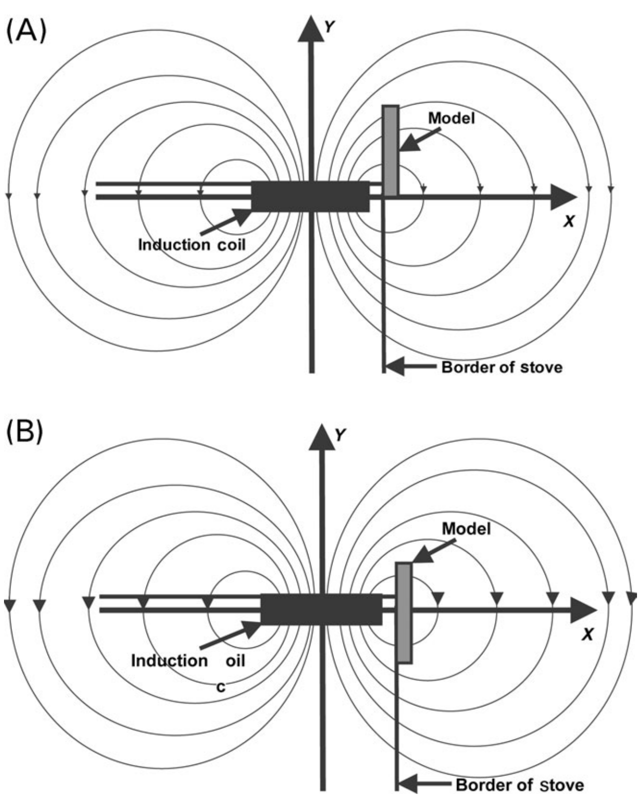

Figure 3 Possible positions of the PP model in closest proximity to an induction cooktop (without pot), with (*A*) maximum induced interference voltage and (*B*) minimum, or nearly zero, interference voltage.

Results

Induced voltages

All voltages induced in our PP model were amplitude-modulated at 100 Hz except in one case, where modulation at 33 Hz was used. The induction frequency varied from 25 to 48 kHz (*Table 1*). In most induction cooktops, we found the current-switching period between adjacent hot plates to exceed 1 s. In this case, pacemaker interference, if above the interference-detection threshold, could result in irregular pacing at the switching rate.

The various voltages measured on the PP model are listed in *Table 1*. Unfortunately, the voltages for concentric positions were not recorded in all of our investigations. If the pots are positioned concentrically, the induced voltage increases with decreasing pot size and is highest with closest proximity. In all cases, however, the measured voltages were below 90 mV ($U_{mean} = 49.6 \pm 26.0$ mV, $n = 6$). With eccentric position caused by displacing the pot backwards, the induced voltages increased with large pots. In closest proximity, voltages up to 800 mV could be induced ($U_{mean} = 270.7 \pm 221$ mV, $n = 11$). In this most unfavourable case of eccentricity, the voltage was reduced to ≤60 mV if a distance of 35 cm (length of forearm) between the edge of the stove border and the thorax was maintained. The choice of 60 mV as boundary value was made because of our experience with the pulse generators investigated in 1995.[4] By the time of that study, all pulse generators with an interference threshold below 70 mV were too old to be still in clinical use.

The relationship of the voltage: horizontal versus vertical position was investigated with one induction cooktop. The result confirmed the assertion made earlier (Theory of Voltage Induction) to the effect that the induced voltage is reduced more with horizontal than vertical displacement. A 10 cm horizontal displacement of the PP model reduced the voltage to 38.5%, whereas the reduction was only to 72.9% with the same vertical displacement. It is plausible, therefore, that body height is of insignificant influence with respect to the results presented in *Table 1*.

The voltages proved to be mostly non-sinusoidal. *Figure 5* shows an example of an induced voltage with a small pot (13.5 cm in diameter) and a displacement of 4.5 cm backwards, with closest proximity of the PP model to the stove. The broken line represents the signal with the third harmonic digitally suppressed.

Investigation of pacemakers

Figure 6 depicts the cumulative distribution of the interference threshold of a population. Peak-to-peak voltages were measured at 24 kHz, amplitude-modulated at 100 Hz. 'Cumulative distribution' in this context means that all interference thresholds were sorted in rising sequence and then correlated with the percentage of devices affected at

Table 1 Summary of results obtained with 11 cooktops of different manufacturers

Cooktop number	$U(d_{min,ct})$ (mV)	$U(d_{min,ect})$ (mV)	d(60 mV) (cm)	f (kHz)
1	n.m.	800	35	25–36
2	n.m.	550	31	28.5–31.2
3	64	360	23	25–40
4	45	384	26	25–40
5	n.m.	185	n.m.	25–40
6	85	145	28	25–40
7	67	160	n.m	25–40
8	n.m.	145	27	25–40
9	n.m.	96	6	34–48
10	30	89	n.m.	25–30
11	6	64	n.m.	28–30
Mean	49.5 ± 26.0 ($n = 6$)	270.7 ± 221 ($n = 11$)	25.1 ± 8.6 ($n = 7$)	32 ± 7 ($n = 11$)

$U(d_{min,ct})$, voltage with closest proximity, pot concentric with coil; $U(d_{min, ect})$, voltage in closest proximity, eccentric pot placement; d(60 mV), distance at which the voltage is reduced to 60 mV with eccentric pot arrangement under worst condition; n.m., not measured.

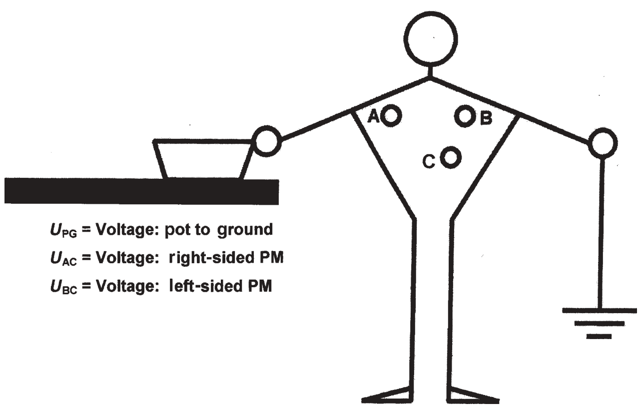

Figure 4 Definitions of voltages when a cooktop user is in simultaneous contact with a metallic pot and ground.

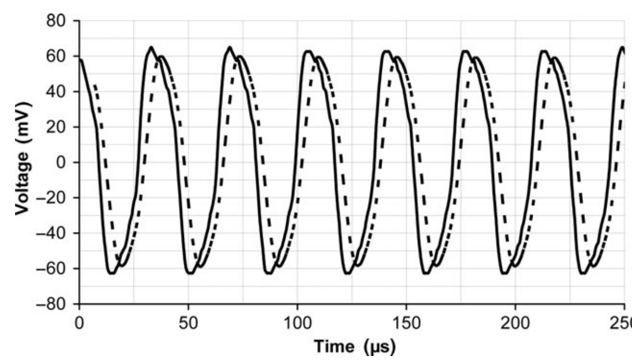

Figure 5 Voltage induced in the PP model of *Figure 1* in closest proximity to the stove, with a small pot (13.5 cm diameter) displaced 4.5 cm backwards from the centre of the induction coil. The broken line represents the signal with the third harmonic suppressed digitally.

this threshold. In this way, we can see what proportion of the population reacts at which interference voltage. The most sensitive pulse generator reacted at 90.5 mV. This threshold was exceptional, as all other devices of that manufacturer reacted at or above 3.5 V. An inquiry revealed that this threshold belonged to an older model that was abandoned in 1998. Because our measuring generator was only capable of voltages up to 4 V, the threshold of 34.4% of the devices could not be tested and a mean value could not be calculated.

An old pulse-generator population we studied in 1995 is described in *Figure 7* in comparison with the new one.[4] The most sensitive old pulse generator was influenced at 32 mV. Below 100 mV, 22 of 217 (10.1%) generators tested sensed interference and reacted by switching to noise mode. However, we estimated that models with interference thresholds below 100 mV were in use by only 1% of the patients living at that time.[4] The mean sensing threshold for the 10.1% subgroup of highly sensitive generators studied in the earlier investigation was 1.94 mV and was 2.12 mV for the best 10%. The mean thresholds for the new population were 3.22 mV for the most sensitive 10% and 3.34 mV for the 34.8% of the generators not reacting up to 4 V. Thus, the immunity to interference voltages is not correlated with higher sensing thresholds.

Investigation of leakage currents

In all volunteers of Group 1, the voltage U_{AC} shown in *Figure 4* was always higher than U_{BC}. This means that interference due to leakage currents is most likely with unipolar, right-sided implants. The voltages between the pot and ground (U_{PG}) and between points A and C (U_{AC}) were always higher for female than for male volunteers ($P < 0.02$). Depending on induction cooktop and pot sizes (the larger the pot, the higher the current), the voltage between pot and ground, when a patient is in contact with the pot, can be as high as 19 V. The capacitive coupling between the induction coil and the pot is highest when the pot is centred over the coil.

The voltages measured were sometimes substantially distorted and were different for load-free and 100 Ω conditions. This made the calculations somewhat problematic, because the fundamental component of the complex waveform had to be estimated. The voltage measured across the thorax was normally far from sinusoidal, as is shown in *Figure 8*. This voltage was measured across a resistor of 1 kΩ between pot and ground. The broken line represents a signal with the third harmonic suppressed digitally.

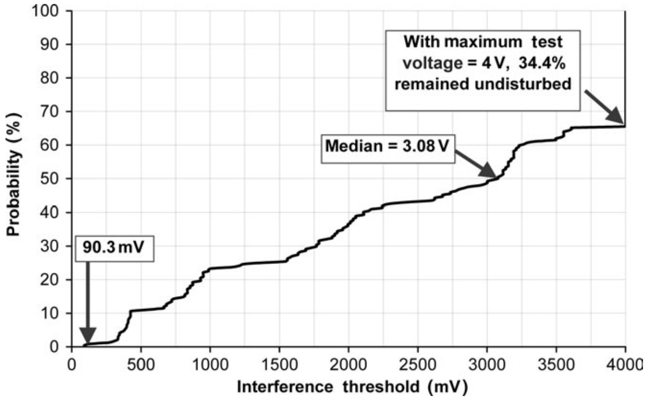

Figure 6 Investigation of the interference threshold of 244 pulse generators implanted between 1998 and 2003 with respect to a 24 kHz signal amplitude modulated with 100 Hz, measured from peak to peak. Cumulative distribution means that all interference thresholds were sorted in rising sequence and correlated with the proportion of pulse generators that were affected at this threshold.

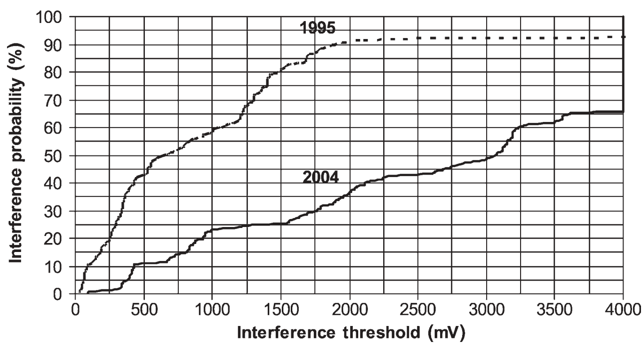

Figure 7 Comparison of interference thresholds measured in 1995 ($n = 217$, upper curve)[4] and 2004 ($n = 244$, lower curve), as described in *Figure 6*.

Table 2 lists the mean voltage U_{ACmean} between points A and C (*Figure 4*), the ratio r of the voltages U_{AC} and U_{PG}, the maximum ratio r_{max} according to Eq. (9), the voltage U_{PG} between the pot and ground in parallel with the current path from hand to hand, and the mean resistance Z_{mean} from hand to hand.

Load-free measured voltages up to 212 V decreased to 4 V when loaded with 1 kΩ, reflecting the high source impedance of $\sim$52 kΩ. The mean leakage current of nine induction cooktops was 5.8 ± 3.8 mA, yielding a voltage of 6.9 ± 4.6 V across 1.2 kΩ.

The investigation with the 10 male volunteers of Group 2 showed that touching a pot with one hand and standing insulated from ground reduced the voltage U_{AC} to a ratio R of 67% at 20 kHz. It can be estimated that this ratio increases to 80% at 30 kHz and to 87% at 40 kHz. This means that touching a pot on an induction cooktop produces leakage currents across the thorax whether the person is grounded or ungrounded.

Discussion

Earlier *in vitro* and *in vivo* studies of pacemaker interference due to induction cooktops yielded contradictory results.[1,2] The *in vitro* investigation found possible interference, whereas the *in vivo* study rejected that possibility. Our study demonstrates that *in vitro* investigations are much better suited to quantifying results physically and searching for worst-case situations. Our theoretical considerations of the mechanism of interference served as guidelines for conducting these trials. The worst-case configuration for interference due to induction is represented by a left-sided, pectorally implanted unipolar pacemaker, with a large pot placed eccentrically on the induction cooktop, the body in closest proximity to the stove, and the apex of the heart just above the level of the induction coil (*Figure 2A*). Pots concentric with the induction coil, even if very small, are not capable of interfering with modern pacemakers (compare *Table 1* with *Figure 6*).

In vivo studies can only yield dichotomous ('yes or no') results without a reliable assessment of the interference threshold. The published *in vivo* study considered a single induction cooktop and 40 patients of whom only two had left-sided implants.[2] This means that the worst case for induced interference voltages was only present in 5% of the patients. Moreover, the patients were studied sitting at a distance of 20 cm from the pot, a position which may resemble that of *Figure 2B*, in which induction is low. The abstract of the other study reports on 31 patients without saying how many of them had unipolar, left-sided implants.[1]

We investigated 11 induction cooktops of different European manufacturers and compared the results with the interference thresholds of 244 unipolar pulse generators implanted after 1997, all of which were treated as left-sided implants. This combination represents 11 times 244, or 2684 separate possible sets of measurements, which would be extremely difficult to carry out with real patients.

Comparing the 24 kHz interference threshold investigations demonstrates the progress in interference rejection of modern pulse generators. *Figure 7* clearly shows that the interference behaviour of the modern population of pulse generators has improved by a factor of 2.8 for the lowest value and 4.65 for the median, in comparison with the population studied in 1995.[4]

With the largest available pot placed eccentrically, up to 800 mV could be induced (*Table 1*) in our PP model when it was positioned as close as possible to the cooktop, a situation which would influence at most 14.8% of the devices depicted in *Figure 6*. Column 3 of *Table 1* proves that progress has been made in induction-cooktop designs, because as the induced voltages in closest proximity with maximum eccentricity $U(d_{min,etc})$ decrease inversely with the

Table 2 Results of leakage-current measurements

Gender	Female	Male
U_{AC}	135 ± 27.6 mV	112 ± 34 mV
U_{PG}	7.7 ± 0.66 V	6.8 ± 0.52 V
r	1.73 ± 0.206%	1.65 ± 0.38%
r_{max}	2.14%	2.14%
Z	1.2 ± 0.1 kΩ	750 ± 57 Ω

U_{AC}, voltage between measuring points A and C in Figure 4; U_{PG}, voltage between pot and ground; r, ratio of U_{AC}/U_{PG} according to Eq. (8); r_{max}, maximum ratio according to Eq. (9); Z, impedance measured from hand to hand.

chronological order of cooktops from oldest (No. 1) to newest (No. 11). At a distance of 35 cm (forearm length), the induced interference voltage under worst-case conditions is reduced to ≤60 mV, which is not problematic for today's pacemaker patients.

Our results can be interpreted as follows:

Pacemaker interference due to the magnetic fields of an induction cooktop can occur only if:

- the patient is as close as possible to the cooktop,
- the pot is positioned extremely eccentrically,
- the patient has a unipolar-sensing pulse generator which was implanted pectorally on the left side,
- the pulse generator is among the most sensitive 14.8% of the population depicted in *Figure 6*.

Under these four conditions, the patient is potentially endangered if she or he is not pacemaker-dependent, because interference by induction cooktops with amplitude-modulated fields invokes asynchronous pacing that may compete with the underlying rhythm. The pacing period could be reduced only if the power is switched from one cooktop coil to another, an event that would very rarely occur.

The more tolerant the eccentricity recognition of the cooktop, the higher will be the voltages that can be induced. It would be helpful, therefore, if the maximum allowable eccentricity was reduced in induction-cooktop designs.

Advice 1. Pacemaker patients should take care to position pots on induction cooktops concentrically with the induction coils.

Leakage currents passing through the body of a unipolar-pacemaker patient can produce interference whether the pulse generator is implanted on the right or left side of the thorax and whether the patient is stirring with a metal utensil within the pot or touching it for a substantial period of time. The larger the pot covering the coil, the higher the interference voltage will be. The results of our leakage-current investigation can be interpreted in the following way.

- For male or female patients, up to 2.1% of the voltage U_{PG} between the pot and ground can be sensed at the input of a right-sided, pectorally implanted pacemaker system.
- To keep this voltage <100 mV (our boundary value for contemporary pulse generators), the voltage between the pot and ground U_{PG} should be limited to 4.7 V to prevent activation of the asynchronous interference mode.

As a rule of thumb, one can estimate that the voltage across the input of a unipolar pacemaker is ∼2% of that between the pot and ground, which has proved to be up to 19 V. Thus a voltage of up to 380 mV could influence 5% of the population depicted in *Figure 6*. Such voltages can be measured easily without patients by means of a 1.2 kΩ resistor connected between the pot and ground. Neither of the earlier studies addressed possible interference by leakage currents.[1,2]

Advice 2. Patients with unipolar-sensing pulse generators should not touch pots on induction cooktops for long periods of time nor use metal utensils.

To summarize, there are two different coupling mechanisms: the magnetic field, which is largest with eccentricity due to stray fields, and the capacitively coupled leakage currents, which are largest with large pots whether placed concentrically or not. Leakage currents, however, can pass through the body only when the pot is touched. The two mechanisms require two different protective measures for pacemaker patients: (i) avoid eccentricity and (ii) do not touch pots for long periods of time.

From our experience with 11 different induction cooktops, we conclude that leakage currents can vary largely, even among different models from one manufacturer. Obviously, existing induction cooktops are not designed to minimize leakage currents.

What proportion of pacemaker systems are left-sided implants with unipolar sensing? The answer is complex because implantation practices differ from one country to another. We know that the mean proportion of implanted unipolar ventricular leads was 43% in 1998 for Western Europe, with Austria, the Netherlands, Spain, and Switzerland below this value.[7] A recently published study for Germany revealed that 47% of 319 ventricular leads of deceased patients with pacemakers implanted in 1998 or later were unipolar.[8] Of the 168 bipolar pacemakers, 16 (9.5%) had unipolar sensing, so the majority (52.4%) was unipolar, and of these 42.5% were implanted in the left-sided pectoral position. The probability of having a unipolar-sensing, left-sided pacemaker is thus 22.3% in Germany, which represents about 78 000 patients, a minority, although not a negligible one, of the 350 000 living pacemaker patients in that country.

The old (1995) CENELEC standard required a sensing threshold for pulsed interference of at least 48 mV at 24 kHz.[6] *Figure 9* shows that the results for pulsed and amplitude-modulated interference thresholds are quite different. All pulse generators are significantly more sensitive to pulsed than to sinusoidally modulated voltages (*Figure 9*). All devices manufactured before 2003, tested and depicted in *Figure 6*, met the old (1995) standard, and only 17.4% failed to meet the new (2003) standard, proving that the new standard does not pose a significant challenge. Obviously, it is not a great problem to make pulse generators resistant to interference at frequencies >10 kHz. However, it is surprising to see the magnitude of the difference between the most and the least sensitive pulse generators. Whether and when the new standard will further elevate interference thresholds and reduce the

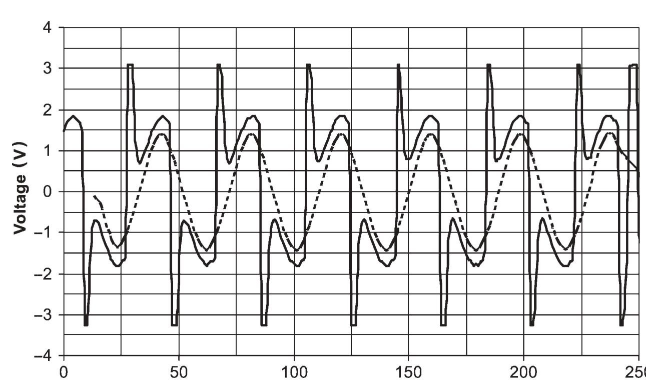

Figure 8 Voltage measured across a 1 kΩ resistance between a 24 cm diameter pot and ground. The broken line represents a signal with the third harmonic digitally suppressed.

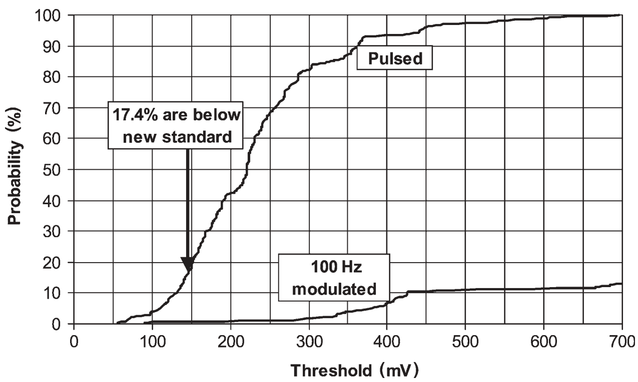

Figure 9 Proportion of pacing systems likely to be affected as a function of the interference voltage measured from peak to peak. All pulse generators were significantly more sensitive to pulsed than to sinusoidally modulated voltages (lower curve). All devices tested met the old standard, but 17.4% failed to meet the new standard.[5,6]

difference between the most and least sensitive devices is an exciting question awaiting an answer.

Limitations of the study

The interference thresholds of 244 pulse generators were tested with 24 kHz sinusoidal voltages. All induction cooktops operated with frequencies of $\geq$20 kHz (*Table 1*) and with induced voltages deviating markedly from sinusoidal waves (*Figure 8*), so that the real thresholds probably differ somewhat from the test results. However, higher frequencies and waves with high harmonic content will yield higher thresholds than with sinusoidal waves of 24 kHz, making the interpretation of the results somewhat pessimistic. We only recently developed a method of reducing the harmonic distortion by filtering out the third harmonic digitally, as is demonstrated in *Figures 5* and *8*. The filtered results are presumably closer to the sinusoidal threshold. Thresholds for frequencies >24 kHz should be higher if any form of filtering is present. The results of voltage division due to leakage currents with the 24 students in Group 1 were obtained with a single cooktop and at a frequency of 32 kHz. The question remains open, therefore, whether volunteers of all ages combined with other cooktops at other frequencies would yield identical or similar results.

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