Magnetic field–induced interactions between phones containing magnets and cardiovascular implantable electronic devices: Flip it to be safe? *e*

Philipp Lacour, MD,*† Phi Long Dang, MD,* Frank R. Heinzel, MD, PhD,*†
Abdul Shokor Parwani, MD,*† Felix Bähr, MD,*† Andreas Kucher, PhD,‡
Felix Hohendanner, MD, PhD,*† Thoralf Niendorf, PhD,§ Faezeh Rahimi, MSc,§
Nandita Saha, MSc,§ Haopeng Han, MSc,§ Kerstin Rubarth, MSc,¶‖
Mohammad Sherif, MD,*† Leif-Hendrik Boldt, MD,*† Burkert Pieske, MD,*†¶**
Florian Blaschke, MD*†

*From the *Department of Internal Medicine and Cardiology, Charité-Universitaetsmedizin Berlin, Campus
Virchow-Klinikum, Berlin, Germany, †DZHK (German Centre for Cardiovascular Research), Partner
Site Berlin, Berlin, Germany, ‡Biotronik SE & Co. KG, Berlin, Germany, §Berlin Ultrahigh Field
Facility (B.U.F.F.), Max Delbrück Center for Molecular Medicine in the Helmholtz Association, Berlin,
Germany, ¶Institute of Biometry and Clinical Epidemiology Charité-Universitätsmedizin Berlin, Berlin,
Germany, ‖Berlin Institute of Health at Charité-Universitätsmedizin Berlin, Berlin, Germany, and
**Department of Internal Medicine and Cardiology, German Heart Center Berlin, Berlin, Germany.*

BACKGROUND Recent case reports and small studies have reported activation of the magnet-sensitive switches in cardiovascular implantable electronic devices (CIEDs) by the new iPhone 12 series, initiating asynchronous pacing in pacemakers and suspension of antitachycardia therapies in implantable cardioverter-defibrillators (ICDs).

OBJECTIVE The purpose of this prospective single-center observational study was to quantify the risk of magnetic field interactions of the iPhone 12 with CIEDs.

METHODS A representative model of each CIED series from all manufacturers was tested *ex vivo*. Incidence and minimum distance necessary for magnet mode triggering were analyzed in 164 CIED patients with either the front or the back of the phone facing the device. The magnetic field of the iPhone 12 was analyzed using a 3-axis Hall probe.

RESULTS *Ex vivo*, magnetic interference occurred in 84.6% with the back compared to 46.2% with the front of the iPhone 12 facing the CIED. *In vivo*, activation of the magnet-sensitive switch occurred in

30 CIED patients (18.3%; 21 pacemaker, 9 ICD) when the iPhone 12 was placed in close proximity over the CIED pocket and the back of the phone was facing the skin. Multiple binary logistic regression analysis identified implantation depth (95% confidence interval 0.02–0.24) as an independent predictor of magnet-sensitive switch activation.

CONCLUSION Magnetic field interactions occur only in close proximity and with precise alignment of the iPhone 12 and CIEDs. It is important to advise CIED patients to not put the iPhone 12 directly on the skin above the CIED. Further recommendations are not necessary.

KEYWORDS Cardiovascular implantable electronic device; iPhone 12; Magnet-sensitive switch; Magnetic field interactions; Magnetic stray field

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Introduction

Cardiovascular implantable electronic devices (CIEDs) such as pacemakers and implantable cardioverter-defibrillators (ICDs) are susceptible to malfunction in the presence of external electromagnetic fields.[1,2] Most CIEDs include magnet-sensitive switches (reed switch, Hall-effect

sensor, giant magnetosensitive resistor, telemetry coil) that respond to external magnetic fields. Clinical magnets can be used to switch pacemakers to an asynchronous pacing mode to prevent inhibition of pacing in case of oversensing and to obtain information about the battery status of the device, as the pacing rate under magnet application is dependent on

battery life. In ICD patients, clinical magnets can be used to suspend antitachycardia therapies without affecting the pacing mode in cases of inappropriate arrhythmia detection.[3]

For protection from static magnetic fields, the International Organization for Standardization (ISO) 14117:2019 standard specifies a limit in magnetic flux density (B field) of 1 mT, up to which magnet-sensitive switches of CIEDs should remain unaffected.[4,5] Unintentional activation of magnet-sensitive switches has been reported in proximity to portable headphones, laptops, and surgical drapes.[6–8] Greenberg et al[9] recently reported the case of a patient in whom ICD therapies were suspended when an iPhone 12 (Apple Inc., Cupertino, CA) was brought in close proximity to an implanted Medtronic ICD. This observation was confirmed by small *ex vivo* and *in vivo* studies demonstrating iPhone 12–induced inhibition of ICD therapy and reprogramming to asynchronous pacing mode in CIEDs.[10,11] The likely reason for this phenomenon is that the recently launched iPhone 12 series contains an annular array of 18 permanent magnets (MagSafe technology) located underneath the wireless charging coil. The magnets adhere the phone to MagSafe-based accessories including cases and chargers.[12] In addition, the magnet array is used to align the iPhone 12 on a wireless charger to increase wireless charging efficacy. Based on these reports of magnetic interference with CIEDs, Apple Inc. recommends keeping the iPhone 12 and MagSafe accessories at least 15 cm away from the devices to avoid any potential interactions.[13]

To analyze the incidence of magnetic interference across all CIED types and manufacturers, we systemically examined the risks and conditions for magnet mode activation by the iPhone12 both *ex vivo* and *in vivo*.

Methods
Study population
Between February and June 2021, a total of 164 patients were prospectively enrolled in the study at our institution (Department of Internal Medicine and Cardiology, Charité-Universitaetsmedizin Berlin). Eligible subjects were patients older than 18 years with a cardiovascular implantable electronic device (CIED). With the exception of 8 cases (6 with subcutaneous implantable cardioverter-defibrillators [ICDs] and 2 with cardiac contractility modulation [CCM] systems), all patients were implanted with a conventional transvenous ICD or pacemaker. The investigation included all types of pacemakers and ICDs (single-chamber, dual-chamber, biventricular). Patients were tested with their CIED programmed to the patient's usual settings.

The study protocol was approved by the human ethics committee of the Charité-Universitaetsmedizin Berlin (Ethics Application No. EA2/105/15) and is in accordance with the Declaration of Helsinki. All patients provided written informed consent. The study was registered at the German Registry of Clinical Studies (DRKS00025140).

Study protocol
The study was a prospective single-center observational study evaluating potential magnetic interference of CIEDs with the iPhone 12. All subjects underwent standard device interrogation to ensure normal operation of all components and functions of their implanted devices. After testing was completed, devices were reinterrogated to exclude magnetic interference–triggered changes in CIED programming. The CIED generator position was characterized by estimating CIED implantation depth according to the following algorithm. In the case of a visible device contour, implantation depth of the generator was estimated in millimeter increments in a range from 0.3 to 0.5 cm. In cases of easily palpable aggregate edges, implantation depth was estimated in 0.5-cm increments in a range from 0.5 to 2.5 cm. In cases where the contour of the generator could not be palpated, implantation depth was estimated in 1.0-cm steps starting from 3.0 cm.

Magnetic interference with the CIED was defined as follows: (1) pacemaker magnet response, defined as switching to an asynchronous pacing mode; (2) ICD magnet response, defined as suspension of ICD therapy; and (3) inactivation of CCM therapy delivery.

Ex vivo and *in vivo* studies
To determine the maximum distance for an iPhone 12–induced activation of the magnet-sensitive switch in CIEDs (pull-in distance), the iPhone 12 was slowly moved toward the surface of the skin above the CIED generator (for *in vivo* tests) or to the device surface (for *ex vivo* tests), following a 3-dimensional grid. As the annular array of magnets is built into the back of the iPhone 12, the tests were carried out with either the front or the back of the iPhone 12 facing the CIED. In cases where a magnet response was detected, the phone was slowly moved away from the skin or device surface to determine the drop-out point (distance for deactivation of the magnet mode). The results were compared against a clinical doughnut magnet (Medtronic Model 9466) with a magnetic field strength of 9 mT at a distance of 3.8 cm from the magnet surface. *Ex vivo* activation of the magnet-sensitive switches in pacemakers was analyzed using a global cardiac simulator. During the *in vivo* tests in pacemaker patients, a 3-lead electrocardiogram (ECG) was used to detect switching to an asynchronous pacing mode. *Ex vivo* and *in vivo* suspension of ICD therapy in transvenous ICDs and S-ICDs from Boston Scientific Inc. was detected by the audible tone from the ICD magnet alarm; from Biotronik using a verification programmer; and from St. Jude Medical (Abbott) and Sorin (MicroPort) by repeated device interrogation. For ICDs from Medtronic, the device programmer was used to display activation of the magnet-sensitive switch in real time.

Analysis of the magnetic stray field of an iPhone 12
To characterize the magnetic stray field of the iPhone 12, measurements of the magnetic flux density (B-field) were

conducted. The flux density of the magnetic field was measured in the x-, y-, and z-directions using a 3-axis Hall probe (MMZ-2508-UH; Lake Shore Cryotronics, Westerville, OH) connected to a gauss meter (Model 460; Lake Shore Cryotronics). B-field data were acquired for transverse planes (x-y plane) with the head of the Hall sensor positioned (z-distance) 1, 5, 10, 15, and 20 mm away from the front or the back of the iPhone 12 using an in-plane spatial resolution of 1 mm. The center of each plane was aligned with the transversal center of the iPhone 12. The Hall probe was attached to a probe holder of COSI (cost-effective open-source imaging) Measure, which is an open-source 3-dimensional multipurpose measurement system that was used to control the sampling trajectory of the Hall probe.[14] All data were saved in a .txt file including the magnetic flux density components Bx, By, and Bz for each sampling point. For each plane, measurements were performed in both the absence and the presence of an iPhone 12 to determine background fields. For data analysis, the magnetic field of the background was subtracted. The total magnetic field was calculated as a vector sum of the magnetic flux density (Equation 1).[15]

$$B_T = \sqrt{B_x^2 + B_y^2 + B_Z^2} \ (1)$$

with B_T being the total magnetic flux density in the x-, y-, and z-coordinates, and Bx, By, and Bz being the magnetic flux density along the x-, y-, and z-direction, respectively. For each plane, the maximum magnetic field strength (B_{max}) was determined. MATLAB R2020a (MathWorks, Natick, MA) was used for data analysis, processing, and visualization.

Statistical analysis

A sample size calculation based on previous studies was not feasible due to the lack of similar data and insufficient sample sizes. Continuous variables are presented as mean ± SD. Categorical variables are given as absolute and relative frequency. At first, univariable regression analyses were performed to select statistically significant variables for possible inclusion in the corresponding multiple regression models. Second, bivariate correlation analysis with Pearson correlation coefficient was performed with the significant variables to examine mutual correlation. In case of Pearson R ≥0.5 between ≥1 variables, only the most informative variable, based on clinical judgment, was included in the corresponding multiple regression model. Subsequently, multiple binary logistic regression was performed with forward and backward selection to identify independent *in vivo* predictors for iPhone 12–induced magnet-sensitive switch activation and to adjust for potential confounders. Multiple linear regression analysis followed by forward and backward selection was performed to determine independent predictive variables for the pull-in distance of a clinical doughnut magnet, adjusting for potential confounders. Missing data (7.9%) only occurred in the *in vivo* pull-in distance to clinical doughnut magnet measurements. Multiple

imputations with fully conditional specifications and 5 iterations were used to impute these missing values. A sensitivity analysis comparing the multivariable regression models before vs after multiple imputations did not show relevant differences. Two-sided $P \leq .05$ was considered significant. Due to the exploratory nature of this study, no adjustment for multiplicity was performed. All statistical analyses were performed with SPSS Statistics Version 27 (IBM Corp., Armonk, NY).

Results

Ex vivo study

The incidence of magnetic interference of the iPhone 12 with a representative model of all CIED series from all manufacturers (Biotronik, Berlin, Germany; Boston Scientific, Marlborough, MA; Impulse Dynamics, Marlton, NJ; St. Jude Medical [Abbott], Saint Paul, MN; Medtronic, Minneapolis, MN; Sorin [MicroPort], Clamart, France) was examined *ex vivo*. Analyzed CIEDs included 10 model series from Biotronik, 8 from Boston Scientific, 9 from Medtronic, 7 from St. Jude Medical (Abbott), 4 from Sorin (MicroPort), and 1 from Impulse Dynamics (Supplemental Table 1). Most modern CIEDs use Hall-effect sensors, giant magnetosensitive resistors, or telemetry coils, whereas older models have built-in reed switches (Supplemental Table 1).

Overall, magnetic interference was more frequent with the back of iPhone 12 facing the CIED (interference rate 84.6 %) compared to the front of the iPhone facing the CIED (interference rate 46.2 %). Notably, no magnetic interference was observed in S-ICDs (Boston Scientific) and the CCM system (Impulse Dynamics). With transvenous CIEDs from Boston Scientific, ICDs from St. Jude Medical (Abbott), and ICDs from Sorin (MicroPort), activation of the magnet-sensitive switch only occurred with the back of the iPhone 12 facing the device (Table 1).

We next analyzed the pull-in and drop-out distances for magnet mode activation by the iPhone 12 in comparison to a clinical doughnut magnet (Figure 1). Activation of the magnetic-sensitive switch by the iPhone 12 occurred at a mean pull-in distance of 3.6 ± 2.9 mm away from the device housing (Biotronik: 2.4 ± 2.2 mm; Boston Scientific: 1.7 ± 1.3 mm; Medtronic: 5.9 ± 3.0 mm; Sorin [MicroPort]: 3.0 ± 1.6 mm; St. Jude Medical [Abbott]: 5.0 ± 3.6 mm). Mean drop-out distance was 7.9 ± 4.6 mm away from the device surface (Biotronik: 5.9 ± 1.8 mm; Boston Scientific: 3.9 ± 0.9 mm; Medtronic: 13.6 ± 3.8 mm; Sorin [MicroPort]: 5.0 ± 1.4 mm; St. Jude [Abbott]: 8.0 ± 2.0 mm). Notably, no hysteresis of the magnet-sensitive switches, defined as the difference between the pull-in and drop-out distances, was observed in CIEDs from Sorin (MicroPort).

An example of iPhone 12–induced suspension of antitachycardia therapy in a Boston single-chamber ICD (INOGEN^TM MINI) in a simulation of ventricular fibrillation using an electronic rhythm simulator (ARSI-4, Bannewitz, Germany) is shown in Supplemental Figure 1.

Table 1   Incidence of *ex vivo* magnetic interference of the iPhone 12 with a representative model of all CIED series from all manufacturers

Manufacturer	CIED type	CIED series (N)	Magnet switch activation by iPhone 12 (% of CIED series)	
			Back facing CIED	Front facing CIED
Biotronik	PM/CRT-P	4	100.0	75.0
Biotronik	ICD/CRT-D	6	83.3	66.7
Boston Scientific	PM/CRT-P	3	100.0	0.0
Boston Scientific	ICD/CRT-D	4	100.0	0.0
Boston Scientific	S-ICD	1	0.0	0.0
Medtronic/Vitatron	PM/CRT-P	5	100.0	100.0
Medtronic/Vitatron	ICD/CRT-D	4	100.0	75.0
St. Jude Medical (Abbott)	PM/CRT-P	3	100.0	66.7
St. Jude Medical (Abbott)	ICD/CRT-D	4	25.0	0.0
Sorin (MicroPort)	PM/CRT-P	2	100.0	50.0
Sorin (MicroPort)	ICD/CRT-D	2	100.0	0.0
Impulse Dynamics	CCM	1	0.0	0.0

CCM = cardiac contractility modulation; CIED = cardiovascular implantable electronic device; CRT-D = cardiac resynchronization therapy–defibrillator; CRT-P = cardiac resynchronization therapy–pacemaker; ICD = implantable cardioverter-defibrillator; PM = pacemaker; S-ICD = subcutaneous implantable cardioverter-defibrillator.

Patient and CIED characteristics

Overall, a total of 164 patients with CIEDs from all manufacturers were tested. Analyzed CIEDs included 75 pacemakers, 10 cardiac resynchronization therapy–pacemakers (CRT-Ps), 30 transvenous ICDs, 6 S-ICDs, 41 cardiac resynchronization therapy–defibrillators (CRT-Ds), and 2 CCM systems from Medtronic, Biotronik, St. Jude Medical (Abbott), Boston Scientific, Sorin (MicroPort), and Impulse Dynamics (Supplemental Table 2). Mean age of the study group was 72.3 ± 13.5 years (69.5% male), with body mass index (BMI) of 27.6 ± 4.8. Estimated implantation depth was 1.5 ± 0.9 cm, with a visible device contour in 54 patients (32.9%).

Clinical iPhone 12–induced magnetic interference

In total, clinically significant magnetic interference between the iPhone 12 and CIEDs occurred in 30 patients (18.3 % of the study population). In all cases, magnetic interference with the iPhone 12 only occurred when the phone was placed in close proximity over the CIED pocket, with the back of the iPhone 12 facing the CIED. Among patients with magnetic interference, 18 (60.0%) were implanted with a transvenous pacemaker, 5 (16.7%) with an ICD, 3 (10.0%) with CRT-P, and 4 (13.3%) with CRT-D. A comparison of the pull-in and drop-out distances of a clinical doughnut magnet and the iPhone 12 for patients demonstrating magnetic interference with the iPhone 12 is shown in Figure 2A. The pull-in and drop-out distances of a clinical doughnut magnet for activation of the magnet-sensitive switch in patients without magnetic interference with the iPhone 12 is shown in Figure 2B. Mean pull-in distance for magnet mode activation by the iPhone 12 was 0.8 ± 1.2 mm away from the skin surface, with a mean drop-out distance of 6.2 ± 3.3 mm. Maximum distance from the skin surface for magnetic interference was 4.0 mm, with a corresponding drop-out distance of 10.0 mm.

Predictors of clinical iPhone 12–induced magnetic interference

In univariable binary logistic analysis, BMI, implantation depth, visible device contour, pull-in distance of a clinical doughnut magnet, device type "pacemaker," Hall sensor, and the CIED manufacturer Medtronic were significantly associated with the incidence of iPhone 12–induced magnetic interference. In the multiple binary logistic regression model after forward and backward elimination, implantation depth (odds ratio [OR] 0.07; 95% confidence interval [CI] 0.02–0.24) and the pull-in distance of a clinical doughnut magnet (OR 2.00; 95% CI 1.42–2.83) were identified as independent predictors of magnet mode activation by the iPhone 12 (Figure 3A).

Furthermore, we separately determined predictors of the pull-in distance of a clinical doughnut magnet. Univariable analysis showed that BMI, implantation depth, visible device contour, iPhone12–induced activation of the magnet-sensitive switch, CIEDs from Biotronik, Boston Scientific, Medtronic, and St. Jude Medical (Abbott), S-ICDs, and the sensor types "Reed," "Hall," and "GMR" (giant magnetosensitive resistor) were significantly associated with the pull-in distance of a clinical doughnut magnet. In the multiple linear regression analysis after forward and backward selection, magnet mode activation by the iPhone 12 (regression coefficient [B] 1.17; 95% CI 0.50–1.84), and CIEDs from the manufacturer Medtronic (B 2.53; 95% CI 2.05–3.02) remained independent predictors of a greater pull-in distance, whereas a greater implantation depth (B –0.43; 95% CI –0.70 to –0.15), and devices from St. Jude Medical (Abbott) (B –1.34; 95% CI –2.26 to –0.43) were predictors for a shorter pull-in distance of a clinical doughnut magnet (Figure 3B).

Magnetic field measurement

Figures 4A and 4C illustrate magnetic field distribution maps (in-plane resolution 1 mm) obtained for a transversal plane
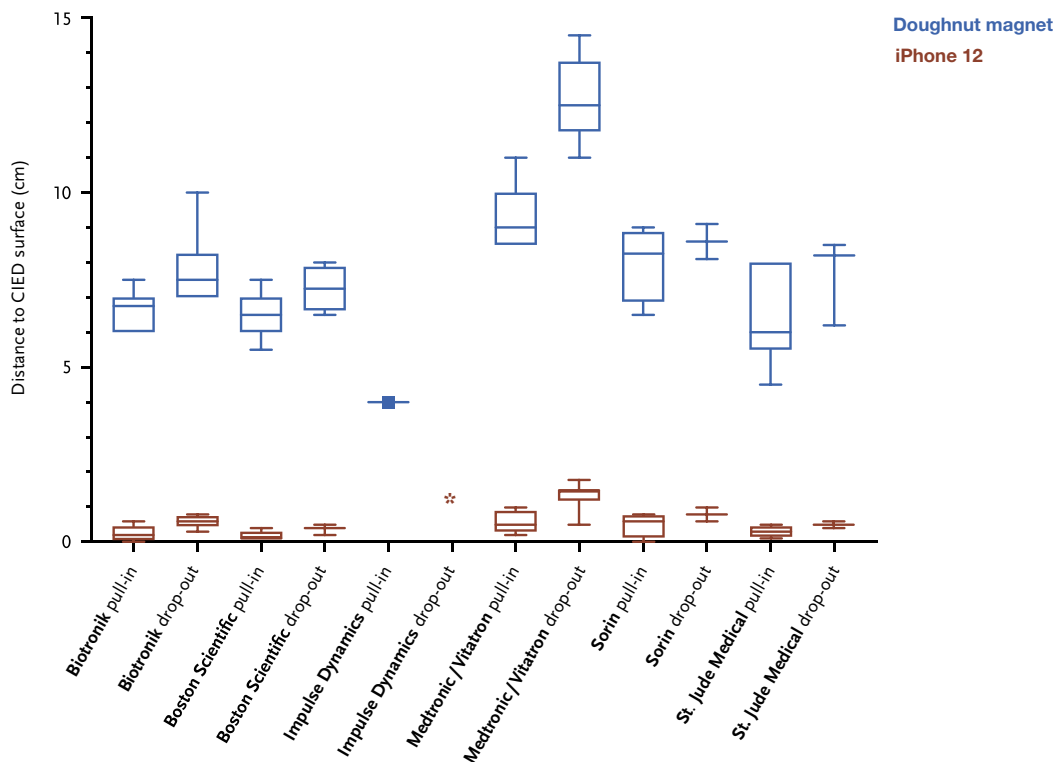
Figure 1   Pull-in and drop-out distances of magnet-sensitive switch activation *ex vivo*. Box-and-whisker plot for pull-in and drop-out distances for activation of the magnet-sensitive switch in cardiovascular implantable electronic devices (CIEDs) by the iPhone 12 with the back facing the device and a clinical doughnut magnet. *Vertical lines within boxes* indicate median values. *Whiskers* and *each half of the box* represent 25% of the data.

positioned at a distance of 1 mm from both the back (Figure 4A) and the front (Figure 4C) side of an iPhone 12. The backside view shows that the strongest magnetic stray field ($B_{max,MagSafe}$ = 17.0 mT) is induced by the annular array of permanent magnets of the MagSafe technology. Compared to the magnetic field distribution on the back, the front of the device shows a much lower maximum magnetic stray field induced by the annular array of magnets ($B_{max,MagSafe}$ = 6.0 mT). Notably, the frontside view revealed stronger magnetic stray fields induced by the wide angle camera, the taptic engine, and the speakers of the iPhone 12. For the front view, the strongest magnetic field strength of B = 20.4 mT was observed around the iPhone's lower right speaker.

Figures 4B and 4D show 3-dimensional distribution maps of the magnetic stray fields derived from the front and the back of an iPhone 12. For the magnetic stray field induced by the annular array of permanent magnets on the back side of the iPhone 12, the $B_{max} \leq 1$ mT limit is reached for a transversal plane located 17 mm from the back side of the iPhone 12. A transversal plane positioned 20 mm from the iPhone's back side yielded B_{max} = 0.74 mT (Figure 4B). For the front side, the magnetic stray field induced by the circular array of permanent magnets, the $B_{max} \leq 1$ mT limit is reached for a transversal plane positioned at a distance of 10.5 mm. A transversal plane positioned 20 mm from the iPhone 12's front yielded B_{max} = 0.48 mT (Figure 4D).

Very rapid decay of the B-fields induced by the wide-angle camera, the taptic engine, and the speakers of the iPhone 12 was observed (Figure 4D). For the bottom speaker, $B_{max} \leq 1$ mT was reached for a transversal plane located 7.2 mm from the front side of the iPhone 12. A transversal plane positioned 20 mm from the front of the iPhone 12 yielded B_{max} = 0.15 mT for the region covering the magnetic stray field induced by the bottom loud speaker (Figure 4D).

Discussion
The main finding of this study is that even with a smartphone having a strong static magnetic field such as the iPhone 12, magnetic responses for all CIED models only occurred with precise alignment and very close proximity of the phone to the device. In addition, we demonstrated that the information obtained from the interaction of any CIED with a routine clinical doughnut magnet and from the quantitative magnetic field map of consumer electronic devices (as provided here for the iPhone 12) allows an accurate estimate of the minimum distance necessary to minimize the risk of magnetic interference.

CIEDs are equipped with magnet-sensitive switches that respond to clinical doughnut magnets. Upon application of clinical doughnut magnets, pacemakers change to an asynchronous pacing mode, and antitachycardia therapies are suspended in ICDs. Clinical application of magnets in pacemaker patients includes prevention of pacing inhibition
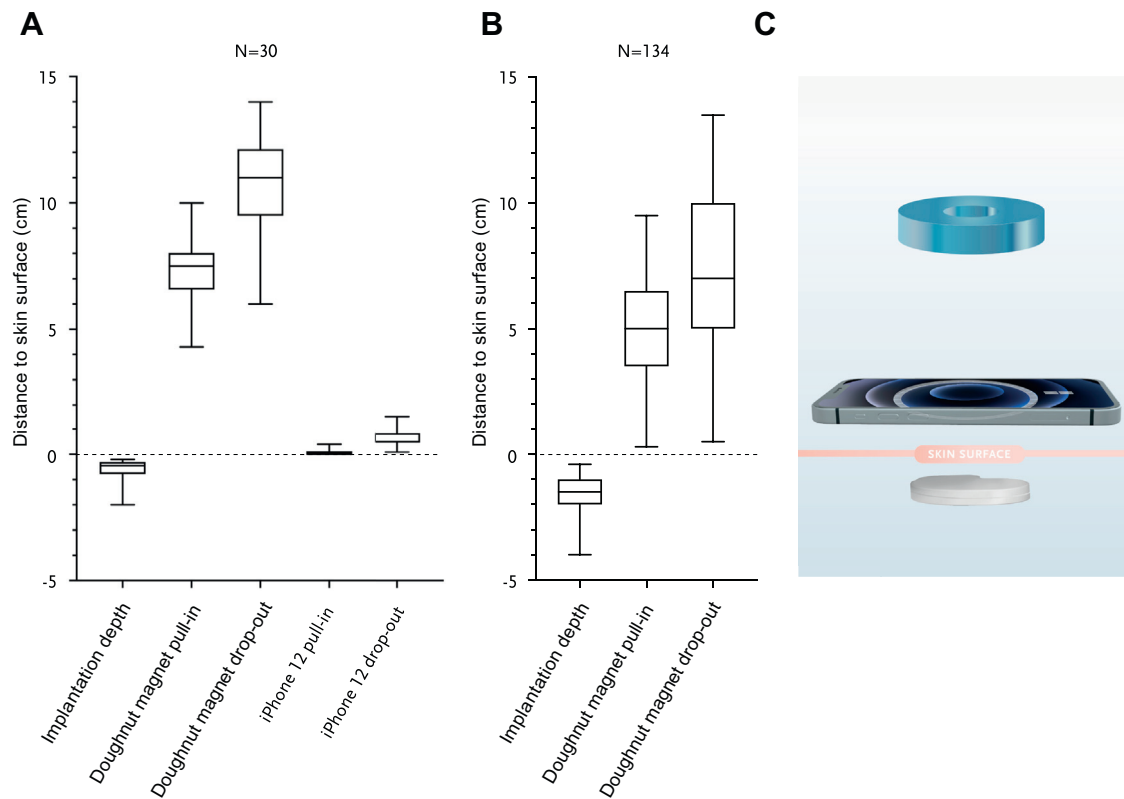
Figure 2 Pull-in and drop-out distances of magnet switch activation *in vivo*. **A:** Pull-in and drop-out distances for initiation of the magnet mode with a clinical doughnut magnet in comparison with the iPhone 12. **B:** Pull-in and drop-out distances for activation of the magnet-sensitive switch of a clinical doughnut magnet in cardiovascular implantable electronic device patients without magnetic interference with the iPhone12. **C:** Graphical representation of the required distance for magnet mode initiation by a clinical doughnut magnet (Medtronic) and the iPhone 12.

in cases of oversensing, and termination of ICD shock delivery in cases of inappropriate arrhythmia detection.[3] Normal CIED function resumes after the magnet is removed. Unintended activation of the magnet mode is a relevant concern for CIEDs with static magnetic fields.[16] As sensing is deactivated in pacemakers in this mode, pacemaker stimuli falling in the vulnerable period of the cardiac cycle could trigger arrhythmias.[17] Suspension of antitachycardia therapies by activation of the magnet mode puts the patients at risk for untreated ventricular arrhythmias.

For protection of CIEDs from inappropriate activation, ISO 14117:2019 and ISO 14708-6 standards require that no magnet mode activation should occur upon exposure to static magnetic fields up to a flux density of 1 mT.[4,5] However, the definition of magnet-sensitive switch activation threshold above 1 mT is at the discretion of the manufacturers. We used a clinical doughnut magnet as a positive control for activation of the magnet-sensitive switch and to create a general reference to quantify the maximal distance for magnetic interference across all CIED manufacturers and models using a standardized magnetic field strength in real-world conditions. Indeed, significant differences were detectable between manufacturers regarding the necessary distance to minimize magnetic interference (Figure 1). The observed differences in magnet sensitivity of CIEDs most likely are

attributable to different settings of the magnet-sensitive switches and may serve as a reference for future studies.

Previous studies with a limited number of CIED models have confirmed that the magnet-sensitive switches in CIEDs are susceptible to interference from consumer electronic devices with built-in magnets.[6–8,18] Neodymium magnets are used in standard mobile phone components such as camera autofocus, speakers, and taptic or vibration units (Figure 4). Most reports have concluded that modern smartphones pose only minimal risk of electromagnetic interference with CIEDs.[19,20] However, recent case reports and small studies have shown unintended activation of the magnetic safety switch by the new iPhone 12 series.[9–11] In this particular smartphone, a circular array of neodymium magnets, built into the back of the smartphone to attach the iPhone 12 to MagSafe-compatible accessories, adds to the magnetic field. These findings raised safety concerns among physicians and patients and prompted a recent Food and Drug Administration warning to keep consumer electronic devices with built-in magnets at least 15 cm away from CIEDs.[21]

In our *ex vivo* tests, analyzing a representative model of each CIED series from all manufacturers, initiation of the magnet mode was dependent on the alignment of the iPhone 12 in relation to the CIED (84.6% with the back vs 46.2% with the front of the iPhone 12 facing toward the CIED).

A Risk of Magnetic Interference with the iPhone 12
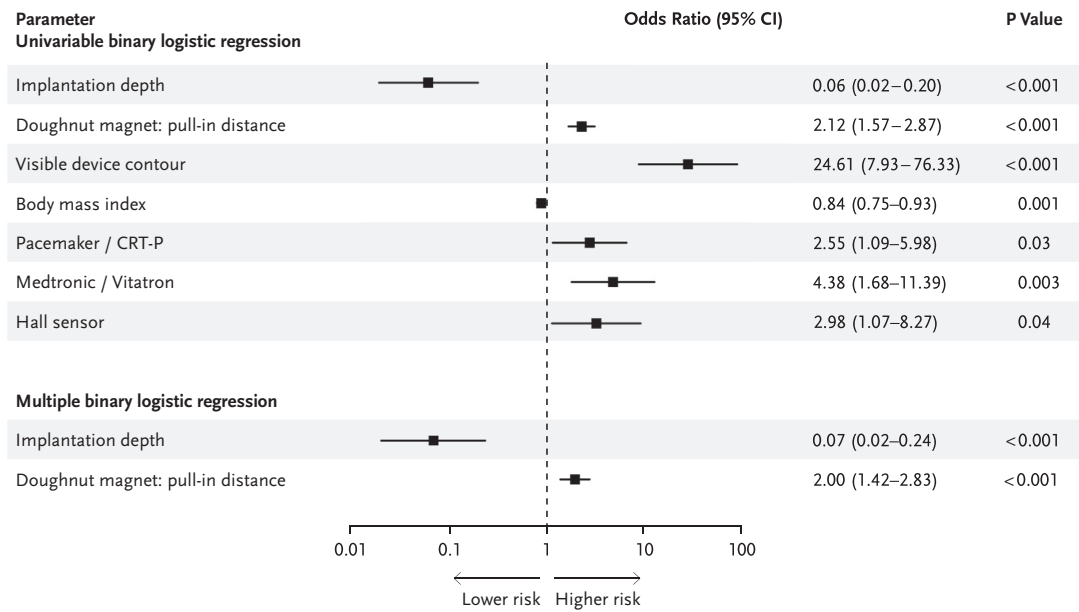
B Parameters correlating with the Pull-in Distance of a Doughnut Magnet
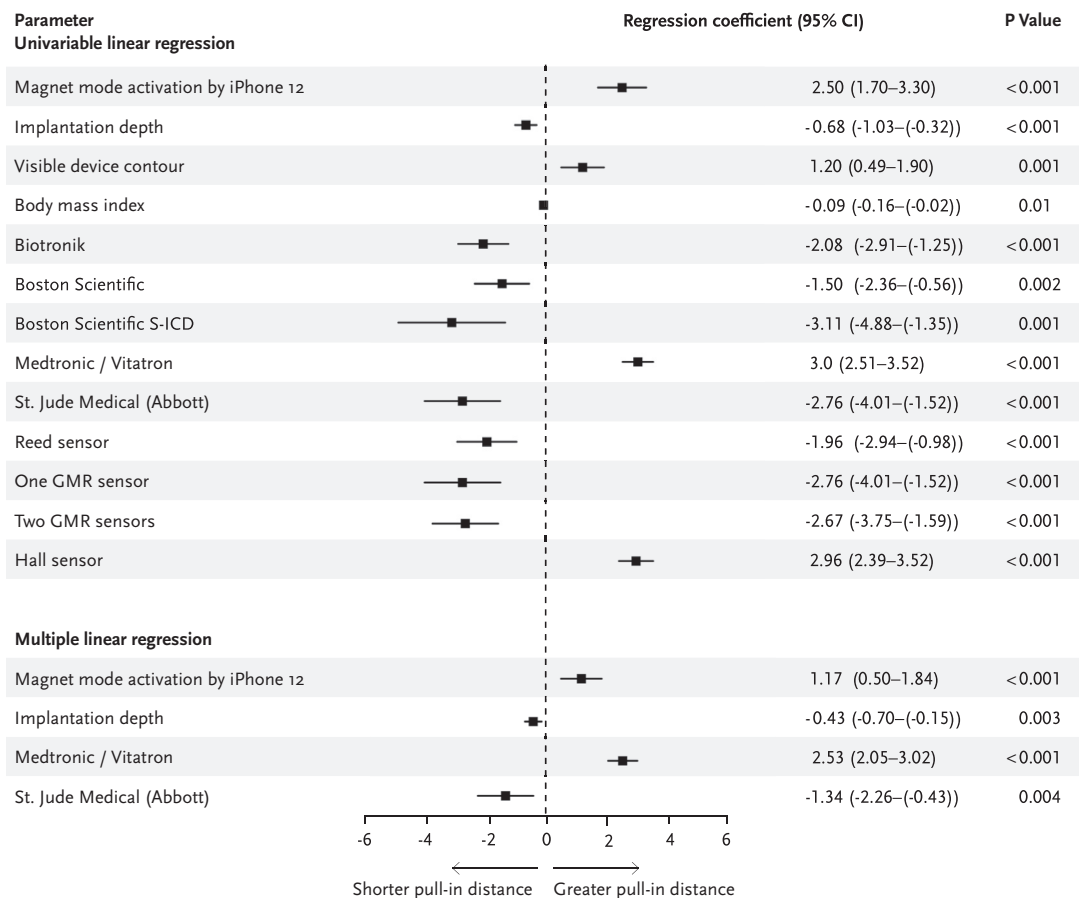
Figure 3 Predictors of clinical magnetic interference. **A:** Significant parameters of clinical magnetic interference between the iPhone 12 and cardiovascular implantable electronic devices after univariable **(top)** and multiple binary logistic regression analysis **(bottom)** after forward and backward selection. **B:** Determinants of a greater pull-in distance of a clinical doughnut magnet after univariable **(top)** and multiple linear regression analysis **(bottom)** after forward and backward selection. Odds ratios are shown for all parameters, with $P < .05$ in the univariable binary logistic regression or univariable linear regression analysis. CI = confidence interval; CRT-P = cardiac resynchronization therapy–pacemaker; GMR = giant magnetosensitive resistor; S-ICD = subcutaneous implantable cardioverter-defibrillator.
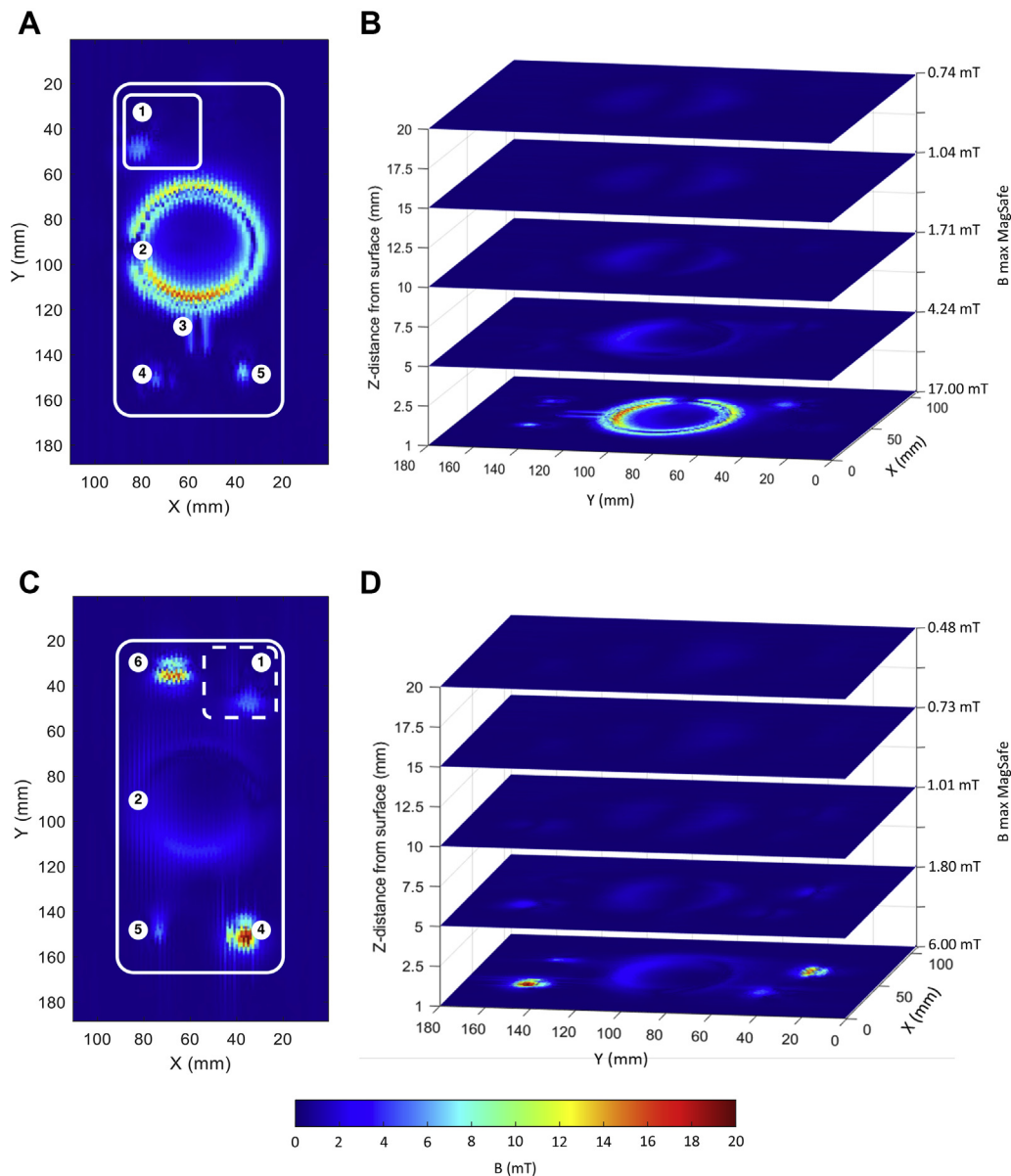
Figure 4 Distribution of magnetic stray fields. **A, C:** Two-dimensional distribution of the magnetic stray field induced by an iPhone 12 for a transversal plane placed at a distance of 1 mm from the back (**A**) and from the front (**C**) of an iPhone 12. **B, D:** Three-dimensional distribution of magnetic stray fields induced by an iPhone 12 for transversal planes placed 1, 5, 10, 15, and 20 mm from the back (**B**) and from the front (**D**) of an iPhone 12. 1 = wide angle camera; 2 = circular array of magnets; 3 = magnetic strip; 4 = bottom speaker; 5 = taptic engine; 6 = front speaker.

Compared to *ex vivo*, magnet mode activation occurred less frequently *in vivo* (84.2% *ex vivo* vs 18.3% *in vivo*). Notably, in all cases with clinical magnet responses, the iPhone 12 had to be placed directly over the CIED pocket with the magnet array in the back directly facing the skin. Multiple binary logistic regression analysis identified implantation depth as an independent predictor of magnet mode activation by the iPhone 12 *in vivo*. Thus, patients with leptosomic constitution may be at higher risk for magnetic interference. Interestingly, no iPhone 12–triggered activation of the magnet-sensitive switch was found in S-ICDs and CCMs.

Currently, Apple Inc. recommends keeping the iPhone 12 and MagSafe accessories at least 15 cm away from CIEDs to avoid any potential interactions.[13] Our 3-dimensional mapping of the magnetic stray field of the iPhone 12 revealed that the circular array of magnets is the strongest magnetic source at the back, and the speaker is the strongest magnetic source at the front (Figure 4). A magnetic field density (B_{max}) ≤ 1 mT limit was reached in a transversal plane located at a distance of 1.70 cm from the back and 1.05 cm from the front of the iPhone 12. These observations and the fact that the magnetic field strength of a dipole magnet, such as the array used in the iPhone 12, is inversely proportional to the cube of the distance explain the low risk of magnetic interference between the iPhone 12 and CIEDs in clinical settings. Accordingly, no magnetic interaction between the iPhone 12 and any CIED has been reported in daily life so far.

Being aware of and advising CIED patients about possible magnetic interactions with consumer electronic devices with built-in magnets such as the iPhone 12 is important. However, such advice should be informed by a careful assessment of the actual risks. Patients should not be given the false impression that they are endangering their lives when using consumer electronic devices; rather, they should be given clear and rational guidelines. This is especially important for patients with ICDs, who often also suffer from psychological distress and worries about their device, resulting in a reduced quality of life.[22]

Study limitations

The current study has several limitations. First, we only analyzed the risk and condition of magnet-sensitive switch activation in CIEDs by the new iPhone 12 series. Thus, we cannot make a statement regarding magnetic field interactions between other smartphone with build-in permanent magnets and CIEDs. Second, while *ex vivo* a representative model of each CIED series from all manufacturers was tested, the 164 CIED patients tested *in vivo* did not include all device series. Third, the CIED implantation depth was estimated according to a specified algorithm and not measured using ultrasound.

Conclusion

The existing recommendation to not put smartphones in a breast pocket on top of a CIED device is reasonable. However, the recommendation to maintain a 15-cm gap between the iPhone 12 and the CIED generator is not necessary and may cause unwarranted concerns. As the number of consumer electronic devices with built-in magnets is expected to increase over time, we endorse a commitment for the manufacturers of consumer electronic devices to provide clear information on the magnet field strength of their products and advocate for standardization of the magnet-sensitive switch activation threshold in CIEDs >1 mT. Ideally, individual testing of CIEDs in patients for magnetic interference with their consumer electronic devices should be performed.

Acknowledgments

Appendix
Supplementary data

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.hrthm.2021.11.010.

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