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Identification of Brugada Syndrome as a Quality Control Test for EMF Danger for Affected Individuals with and without Implanted Devices or Unaware of their Condition

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Abstract: We report three cases of workers with Brugada syndrome (BrS) who were fitted with an active implantable medical device (AIMD) with a defibrillator effect. In these individuals, abnormalities in sodium ion channels are the cause of acute ventricular fibrillation attacks. While the fundamental role of ICD therapy in preventing fatal arrhythmias in Brugada syndrome is obvious, device-related complications cannot be ruled out, especially in younger, working-age patients, even in cases where thoracoscopic epicardial ablation was performed in addition to the ICD with a positive outcome. However, while it is obvious in these individuals, limiting or excluding excess exposure to electromagnetic field (EMF) sources or other incompatibilities with the routine performance of certain tasks is necessary, based on necessary precautions. However, it appears difficult to diagnose Brugada syndrome or other channelopathies in subjects without device use and with an unresolved medical history, or to rule out the effect of exposure to (EMF) in those with unrecognized Brugada syndrome. The goal of this study is to clarify which specific measures could be adopted, whether they are sufficient in the most severe conditions, and whether precautionary procedures allow for continued work. Finally, it is also important to clarify a larger clinical study in the preventive phases.

Keywords: Brugada syndrome, active implantable medical devices (AIMD), electromagnetic fields (EMF).

INTRODUCTION

Brugada syndrome is a highly correlated inherited disease with an increased risk of sudden cardiac death (SCD) [1,2] and is characterized by electrocardiographic findings of right bundle branch block and ST segment elevation in the right precordial leads (V1-V3) [3]. It can manifest spontaneously or after pharmacological induction and may be asymptomatic. Sometimes it is highlighted during cardiological examinations such as sporting activities or checks for work suitability. Family screening with severe symptoms typical of BrS such as syncope, cardiac arrest, SCD in a blood relative have been manifested. BrS is a genetically determined disease that predisposes to various arrhythmological manifestations, due to ventricular fibrillation (VF) or ventricular tachycardia (VT). Usually, it becomes evident between 25 and 50 years, causing at least 4 % of all sudden deaths and - among these - 20 % of deaths with apparent absence of evident cardiac structural alterations [4]. Affected individuals have a male/female ratio of 8:1.

BrS is also a predictor of other cardiac disorders, such as early repolarization syndrome and arrhythmogenic right ventricular cardiomyopathy/dysplasia. The latter is an inherited myocardial disease characterized by fibro-fatty replacement of the right ventricular myocardium and associated with paroxysmal ventricular arrhythmias and SCD [5,6], due to the progressive conduction defect (Lenègre syndrome) [7,8], long Q-T syndrome [9,10], Wolff-Parkinson-White [11], hypertrophic cardiomyopathy [12], atrial flutter [13] and atrial fibrillation [14].

In addition to these aspects, BrS is also associated with non-cardiac pathologies such as epilepsy, thyroid dysregulation, tumours, skeletal muscle sodium channel pathologies, laminopathies and diabetes [15-17]. The reason for these associations may be the abnormal functional expression of sodium channels that makes the pathogenesis of cardiac tissue like that of other types, also based on the evidence of the common BrS gene mutation sodium voltage-gated channel alpha subunit 5 (SCN5A). In fact, this most mutated gene found in BrS is present throughout the body, with the highest levels of protein expression found in plasma, heart and pancreatic juice [18-20]. BrS typically has ST segment elevation in V1–V3 (Brugada pattern type 1), while the mutation appears in 35% of cases and is considered autosomal dominant, affecting the SCN5A gene in 50 % of cases.

The presence of AIMDs raises concerns in cases where subjects are exposed to high-intensity EMFs - e.g. industrial machinery - but also in domestic environments, both conditions that can interfere or deactivate the functioning of the device. On the other hand, the study of the direct effects of EMFs on cardiac cells or on subjects not wearing AIMDs appears limited. The importance of ion channels and in particular the sodium channel is fundamental for the normal electrical flow in the myocardium and for the correct conduction of electrical impulses. Although there is insufficient experimental evidence that EMFs specifically influence these channels in subjects not wearing AIMDs, a precautionary principle is consolidating according to which exposure to magnetic fields of significant intensity can alter the electrical activity of the heart in individuals who already present abnormalities in ion channels.

In summary, starting from the assumption that in healthy subjects there is no significant impact with EMFs, it must be supposed that in those affected by BrS - even if they are not aware - there is an altered electrical conduction substrate that makes them potentially more vulnerable to any external factor that can influence electrical activity, configuring a greater risk. In this sense, the description of the reported cases and the considerations on the risk conditions that can occur in different types of exposure and different intensities and frequencies, push us to affirm that exposure to electromagnetic fields should never be neglected and if it appears experimentally highlighted (26) a modulating effect on the cardiac rhythm and therefore is not the cause of arrhythmias, it can however act as a final triggering factor in genetically predisposed individuals, like the Brugada bearers.

MATERIALS AND METHODS

Case Studies

Following, we describe the clinical pictures of three cases. The subjects involved work in industrial environments with sources of EMFs:

Case I

The first patient, a head chef of a company, was affected by a complex pathology: “Transient ischemic attack and sylvian ischemia in a subject following Implantable Cardioverter Defibrillator (ICD) ablation for BrS and closure of patent foramen ovale (PFO) by Amplatzer, hypercholesterolemia, hyperhomocysteinemia, hypertension, reported polyarthralgia of the lower limbs and lumbar spine, hypotrophy of the left frontal bone table, obstructive sleep apnea syndrome disorders and post-traumatic stress disorder”. Anamnestic data showed that the patient, after finishing his work shift felt a sensation of weakness and reduced sensitivity in the right hemibody. The symptom started from the right lower limb distally and quickly spread to the ipsilateral upper one. He lost his balance and fell to the ground, without being able to move the right side of his body. After a few minutes of immobility, he recovered spontaneously and quickly. He had had for the last 10 years occasional snoring at night, probably complicated by respiratory pauses. The neurologist concluded with the diagnosis of “Possible transient ischemic attack. Suspected obstructive apnea syndrome”. Cranial computed tomography scan showed only a deep incision with clear edges in the left frontal bone internal tissue, not related to concurrent or past trauma. Instead, the Magnetic Resonance Imaging (MRI) showed vague areas of gliosis at the height of the peritrigonal regions and in the left frontal area, just at the limits of appreciability. Later the neurologist suggested to recover him at a cardiology center. Ajmaline test was performed compatible with BrS pattern type 1. It was decided to implant an ICD by cannulating the left subclavian vein. After inserting an electrocatheter (Biotronik Protego DF-1 ProMRI Dx) at the right ventricular level (septal apex) fixing with a muscle band, it was connected to the generator (Biotronik Itrevia 7 VR-T Dx), achieving in this way a subclavicular left pocket, that is still present. The position of the electrocatheter at the tip of the right ventricle (single-chamber ICD, or ICD-VR) was verified under fluoroscopic guidance (X-rays). Subsequently, he accessed neurology for a further cerebral ischemic episode treated with thrombolysis, accompanied by hypokinesia of the lower right facial muscle. BrS type 1 and PFO were confirmed, in addition to hyperhomocysteinemia. Discharge diagnosis was “Vague right sensorimotor syndrome due to left Silviana ischemia in a subject with BrS (carrier of defibrillator) and PFO. Hypercholesterolemia”. The MRI performed subsequently showed small malacial sequelae on a probable previous ischemic basis involving the left cerebellar hemisphere. In the first hypothesis of previous ischemic significance a small focus of nonspecific gliotic appearance involves the left frontal subcortical white matter. Since these were embolic phenomena due to the PFO he went through percutaneous closure surgery by positioning an Amplatzer device. In cardiology department he underwent epicardial ablation of the arrhythmogenic substrate of BrS. Electrophysiological study (EES) and Ajmaline test were negative and highlighted the actual success of the procedure. These checks also confirmed the good prognosis. Finally, the patient was informed that the defibrillator poses some limitations in workplaces and therefore had to avoid using microwave induction equipment, heat sources and chemical agents.

Case II

The subject was a metalworker assigned to numerically controlled turning machine at an agricultural manufacturing company. He presented secondary electrocardiographic alterations to anomalies of the ion channels connected to ion channel abnormalities, which are potentially capable of complicating with VF episodes. This condition is prevented by an ICD implant. The cardiology visit demonstrated, in addition to hypertension, an Electrocardiogram (ECG) with BrS-like aspect in V1-V2. This confirmed a BrS type 1 pattern and mild mitral insufficiency. The endocavitary EES was positive for reproducible induction of VF. Therefore, it was suitable insertion of a single-chamber ICD implant, compatible with MRI in a patient with a spontaneous BrS type 1 ECG pattern with inducibility at the EES and a family history of sudden death (device: Medtronic Evera MRS SR – right ventricular catheter Medtronic 6935M). In opinion of the occupational medicine specialist there are constraints: avoid work involving muscular efforts (manual handling of loads – MHL > 20 kg) or presence of electromagnetic fields (EMF). In summary, the role of metalworker as a numerically controlled lathe operator is partly tolerated, but it is limited in implementing a different technological cycle or adapting to other tasks.

Case III

A worker assigned to electromechanical processing at a steel mill, an environment in which associated dangers and risks are EMF, artificial optical radiation, working at heights > 3 m, inadequate microclimate, dust, fumes and gases, MHL, biomechanical overload of the upper limbs, incorrect postures and confined spaces. Following a cardiological visit, the patient was diagnosed with BrS type 1 pattern. A dual-chamber Abbot ICD device was implanted in consideration of a family history of sudden death. Even in this case the assessment of suitability for work involves limitations. In fact, it implies electromechanical maintenance work which is incompatible with activities to be carried out throughout the industrial plant.

Table 1 provides a summary of clinical-instrumental data necessary to identify the best carriers of AIMDs.

Table 1: Clinical-instrumental data analyses of active implantable medical devices carriers

Case:	I	II	III
Diagnosis: Brugada syndrome (BrS)	Pattern 1	Pattern 1	Pattern 1
Mild Cognitive Impairment (MCI)	No	Yes	Yes
Patent Forament Ovale (PFO)	Yes	No	No
High Blood Pressure	No	No	Yes
Sylvian Ischemia (SI)	Yes	No	No
Electrocardiogram (ECG)	V1 - V2	V1 - V2	V1 - V2
Arrhythmogenic Substrate Ablation	Yes	No	No
Septal Occluder PFO	Amplatzer (nitinol)	No	No
Implantable Cardioverter Defibrillator (ICD)	Biotronic Itrevia 7VR-Tdx	Medtronic Everia HRS-SR	Abbot dual-chamber ICD

Basic Restrictions and Reference Levels

Effects on health by EMF depend on their frequency. In Table 2 we report their classification with some examples, while in Table 3 are the main effects observed and the physical quantities of reference. Common household appliances are widespread and use low frequency magnetic fields (mainly 50 Hz). In contrast, most popular smartphones operate on several frequency bands between 700 MHz and 2,6 GHz. Furthermore, contact currents must be considered, which can cause indirect damage. It is therefore clear that BrS patients must be protected from EMFs in all situations.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) published some different guidelines, respectively for limiting exposure to static and time-varying magnetic fields below 1 Hz [21], electric fields induced by movement of the human body in a static magnetic field (SMF) and by time-varying magnetic fields below 1 Hz [22], time-varying electric and magnetic fields (1 Hz – 100 kHz) [23] and electromagnetic fields (100 kHz – 300 GHz) [24].

Table 2: Classification of some representative electromagnetic field sources

Radiation type	Range of frequencies	Example sources
Static Magnetic Fields (SMF)	0 Hz	Nuclear magnetic resonance (NMR) Electrolytic cells
Extremely Low Frequencies (ELF)	1 Hz – 3 kHz	Overhead and underground power lines Electrical cabins (50/60 Hz) Power equipment
Very Low Frequencies (VLF)	3 kHz – 300 kHz	Atmospheric discharges (lightning)
Radio Frequencies (RF)	300 kHz – 300 MHz	Broadcasting Soft tissue healing appliances
Microwaves (MW)	300 MHz – 300 GHz	Radartherapy Microwave ovens

Table 3: Symptomatic biological effects at different electromagnetic frequencies

Radiation type	Observed effects	Dosimetric quantity	Operational quantity
SMF	Interference with active implantable medical devices (AIMDs) Dizziness, nausea, metallic taste and magnetophosphenes	Internal Electric Field	Magnetic field
ELF/VLF	Electrical stimulation of cells due to currents induced in the tissues	Internal Electric Field	Magnetic field Electric field
RF/MW	Localized overheating of organs and tissues due to absorption of electromagnetic energy	Specific absorption rate (SAR)	Magnetic or electric field

The main objective was to establish regulations for reducing EMF exposure, providing protection against adverse health effects. The risks taken into consideration concerned mainly transient nervous system responses, including peripheral (PNS) and central (CNS) nerve stimulation, induction of retinal phosphenes and possible effects on some aspects of brain function. These guidelines referred to occupationally exposed workers, but also to people who were part of general public. In addition, there was necessary to take into account some workers who, for health reasons, required greater protection than others and should be treated with special restrictions. These guidelines have been implemented into the European Directive on the Minimum Health and Safety *Requirements regarding the Exposure of Workers to the Risks arising from Physical Agents (Electromagnetic Fields)* [25].

The best quantities to describe basic restrictions (BRs) are Internal Electric Field (IEF) for extremely (ELF) and very (VLF) low frequencies (1 Hz – 300 kHz) and Specific Energy Absorption Rate (SAR) for radiofrequencies (RF) and microwaves (MW) in the 300 kHz – 300 GHz range. Figure 1 reports BRs for electric and magnetic fields exposure from 1 Hz to 10 MHz. The trends of IEF restrictions for both PNS and CNS are shown. There may be other factors to consider such as overlapping BRs components in the range between 100 kHz and 10 MHz. For a more detailed discussion see [23,24].

Reference levels (RLs) provide a mean of demonstrating compliance using quantities that are more easily assessed than BRs, assuring at least an equivalent level of protection to the BRs for worst-case exposure scenarios. These RLs are the electric field strength (E) and the magnetic field strength (H). For VLF/ELF sometimes it is preferred to consider the magnetic flux density (B) instead of H. For frequencies higher than 30 MHz there is another RL, corresponding to incident power density (S).

The real protective utility is the danger encountered for a graduation of the subjects for which we want to proceed, which is in practice the difficulty to overcome and requires greater commitment.

Group	**Main risk**	**Overall danger**
Identified carrier (no device)	Arrhythmia triggering	▫ Low-moderate
Identified carrier with ICD/pacemaker	Device interference + arrhythmia	◍ Moderate-high
Unidentified subject	Unprotected lethal arrhythmia	◍ ◍ Potentially highest

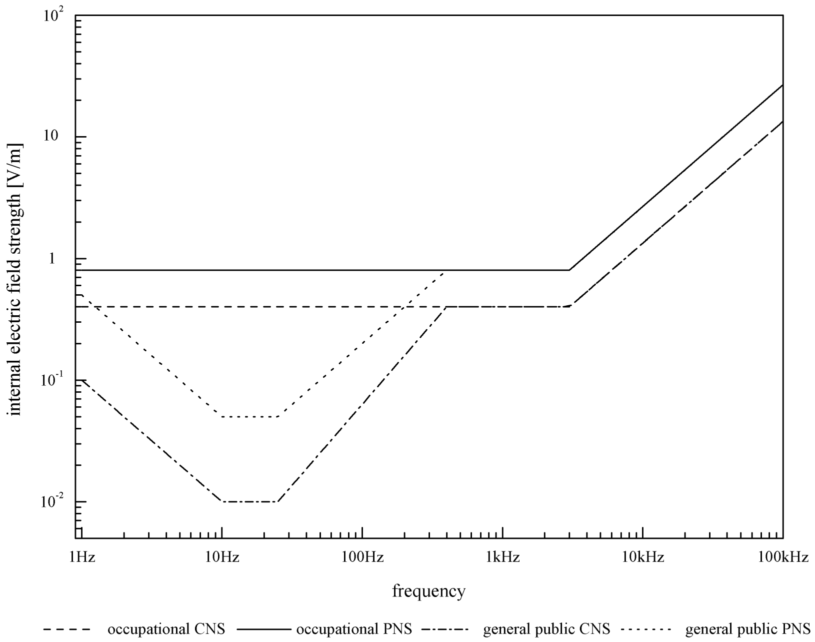
It is absolutely certain that electromagnetic fields, in reality, have no clinical evidence, nor is there a justifiable mechanism of action, much less epidemiological evidence. Electromagnetic fields could be considered modulators, but not triggers. Interference with myocardial tissue in terms of variations in the tissue magnetic field in the pico-Tesla range does not increase the risk of sudden death: the magnetic field generated by cardiomyocytes at the thoracic surface (MCG) is ~10–100 picoTesla (10^{-11}–10^{-10} T), while the intracellular field is smaller and generated by ionic currents, primarily Na^{+} during depolarization.

In summary, the risk in Brugada syndrome is not determined by the intensity of the cardiac magnetic field, but by electrical instability at the cellular and tissue level.

In this mode: in studies of Brugada syndrome, evidence of sodium channel dysfunction is the basis, but acute and severe arrhythmias depend on the balance of calcium and potassium currents. In the electrically vulnerable myocardium, even weak external electromagnetic fields—within accepted safety limits can theoretically modulate the gating of Ca^{2+} and K^{+} channels and the repolarization reserve, potentially contributing to arrhythmogenesis in critical conditions as inherited cardiomyopathies (es. dilated cardiomyopathy familial, mitochondrial cardiomyopathies), cardiac channelopathies (es. Brugada syndrome, progressive cardiac conduction disease, long QT syndrome), structural and vascular Disorders (es. thoracic aortic aneurysm/dissection e.g., Marfan, Loeys-Dietz, congenital coronary artery anomalies familial cases, muscular dystrophies with cardiac involvement).

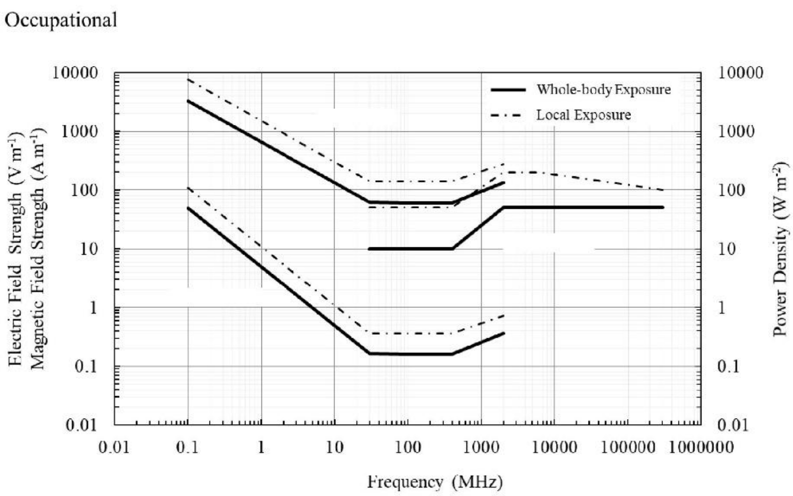
Under these conditions, we shouldn't underestimate the Purkinje cells, which are responsible for highly excitable conduction. They are theoretically more sensitive to electrical stimuli than contractile cardiomyocytes, for high density of ion channels, long action potential, capacity for automaticity, amplified response to ischemia and $Ca2^{+}$, direct connection with the ventricular myocardium. Alterations in ion channel conductance influence the timing and generation of action potentials, suggesting that magnetic fields can modulate neuronal behaviour (44)

☞ They are perfect arrhythmic triggers



<u>Figure 1</u>: Basic restrictions exposure to whole body time-varying electric and magnetic fields from 1 Hz to 100 kHz, respectively for occupational/general public central nerve stimulation (CNS) and for both peripheral nerve stimulation (PNS) and other tissues of head and body (adapted from [23])

Figures 2 and 3 show the RLs respectively for ELF/VLF and RF/MW occupational and general public exposure to time-varying electric and magnetic fields.



<u>Figure 2</u>: Reference levels for occupational and general public exposure to ELF/VLF (adapted from [23])

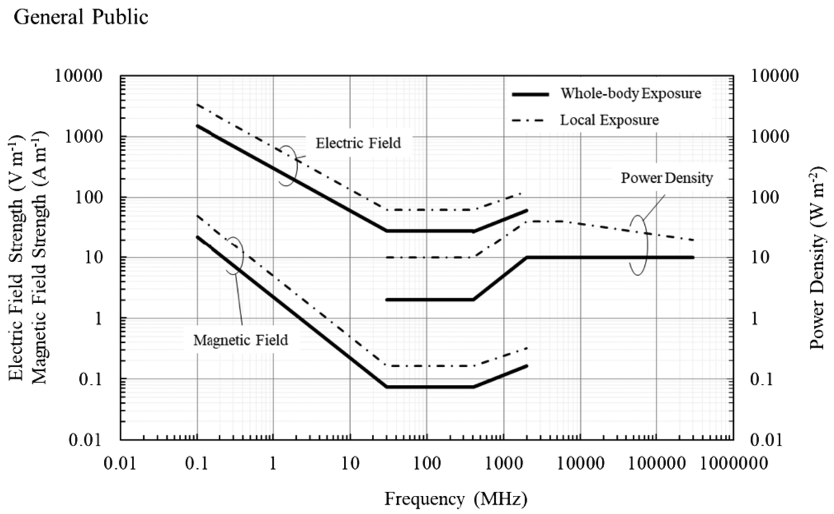


Figure 3: RF/MW reference levels (≥ 6 min) for whole-body occupational and general public exposure to incident electric field strength (E), incident magnetic field strength (H) and incident power density (S) [24]

Safety of AIMDs

Among AIMDs, pacemakers (PMs) regulate cardiac rhythm connected to the myocardium by electrodes, but sometimes they are made by wireless devices for remote control and battery charging. Although these improve monitoring and have fewer side effects, it must be investigated to what extent they can be considered safe in terms of patient protection. Experimental studies [26] have shown that low-frequency fields interact with cardiac rhythm. In patients with paroxysmal atrial fibrillation (AF), low level EMF (LL-EMF) stimulation results in shorter episodes of pace-induced AF and a reduced probability of spontaneous activation, which initiates an AF episode. The exact mechanism by which EMF-exposed patients respond depends on various parameters that increase uncertainties, especially in the interindividual variations in the molecular weight of targeted vagal mediators, namely the levels of TNF-a, IL-6, IL-8 and MCP-1 compared in the two groups.

This work refers to a human experiment and recalls the principle that for a molecule of mass m it is possible to specify what is the intensity and frequency of an applied magnetic field of the device, capable of interfering by increasing the energy of the molecule to carry out the biological action.

The field intensity is calculated using the relation [27]:

$$m\, c^2 = B\, v\, L\, q$$

where c is the speed of light, v is the inertial velocity of the molecule of mass m, L is the length of the biosystem component of the patient, and q is the unity of charge.

We are in the picoTesla (pT) and femtoTesla (fT) range, i.e. extremely small values. This circumstance suggests strongly sensitive biological components that influence the cardiac function. Our cases are certainly complex because BrS is determined by anomalies and reduced efficiency of ion channels (protein channels) present in cell membranes, which facilitate the selective transport of ions through them. They are essential for the electrical potential and for the transmission of impulses. Therefore, they can be *'open'* or *'closed'*, respond to variations in membrane potential and consequently to the relative transmission of the signal. In summary, the regulation of ion transport requires specialized proteins.

Although the initial discovery of mutations in the SCN5A gene provided valuable insights, BrS is now recognized as a multifactorial disease influenced by multiple loci and environmental factors, challenging the traditional autosomal dominant inheritance model. This new comprehensive review aims to provide an up-to-date understanding of BrS, focusing on its pathophysiology, genetic mechanisms and novel risk stratification models. Advances in these areas have the potential to facilitate early diagnosis, improve risk assessment, and enable more targeted therapeutic interventions [28].

To determine the particular sensitivity of ICDs in the human body, which have an extremely weak signal to magnetic and electromagnetic fields compared to terrestrial ones, magnetoneurography (MNG), magnetospinography (MSG), magnetomyography (MMG), magnetocardiogram (MCG) and magnetoencephalogram (MEG) are used. To detect such a signal, highly sensitive magnetic field sensors (SQUIDs) are needed. They are the ones that meet the detection requirements in sensitivity, bandwidth and time response. Recently, other types of magnetometers or gradiometers have been developed for bio-magnetic field detection, with the aiming to overcome limitations of SQUIDs. Among these, optical pumped atomic magnetometers, but they are limited by their bandwidth and cannot meet all neuromuscular magnetic field signal tests, but they can detect the magnetic field signals of some muscles or nerves [29]. Biomagnetic signals characteristics and sensor sensitivity relationship are reported in Figure 4 [30], while in Table 4 we report the bio-magnetic signal features for different sources [31]. The advantage in the use of these technologies is that, since tissues are non-magnetic, magnetic fields propagate in an uninterrupted manner towards the skin surface where they are eventually collected, while electric fields are strongly impacted by the complex permittivity of biological tissues.

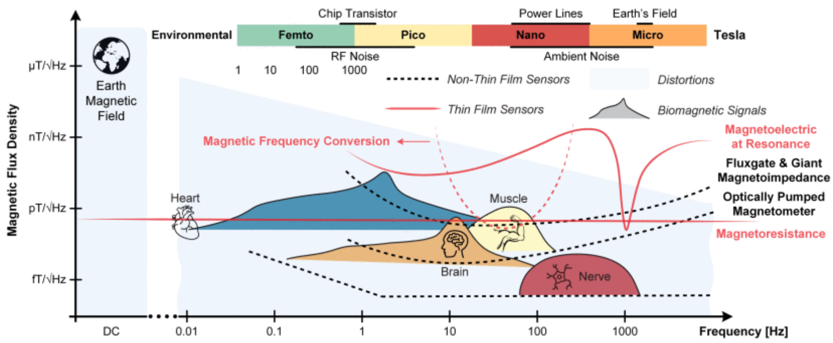


Figure 4: Comparison of amplitude densities of magnetic signals generated by various sources of the human body, with limits of detection of different magnetic sensor types. (extracted from [30])

At this point we cannot exclude that LL–EMFs interfere with the molecular magnetic moments of their electrons or other asymmetric structures, which could be affected by an external magnetic field. Likewise, ion channels also respond to these fields, due to the distribution of their electrons or their molecular structure. Experimentally, this research pushes towards studies that consider the BrS anomaly as significant, in terms of applicative acquisition.

Table 4: Biomagnetic signal features from different tissues

Source	Technology	Magnetic flux density	Frequency (Hz)	Bandwidth (Hz)
Brain	MEG	100 fT – 1 pT	0,5 – 500 (clinically relevant < 70)	~ 500 (70)
Heart	MCG	50 – 100 pT	< 75	75
Nerve	MNG	5 fT – 8 pT	6 – 500	494
Spine	MSG	1 – 100 fT	100 – 5000	4900
Hand / Leg / Head / Muscle	MMG	1 fT – 1 pT	1 – 300	300

f = Frequency in Hz

RESULTS

Health Effects on BrS Workers

The first factor to take into consideration is whether the effects are direct or indirect, as the mechanisms involved in the cause-effect relationship are different. Indirect effects are attributed to the possibility of interference with AIMDs or other devices worn on the body, that can generate mechanical defects due to contact currents. Direct effects, on the other hand, are attributable to a stimulation of nervous structures, in particular neurosensory, and muscular structures that, at high frequencies, produce heating of organs and tissues. In this context appear subjective symptoms such as vertigo (sensation of instability), phosphenes, epilepsy, and disorders affecting the cardiovascular system.

The ICNIRP Guidelines highlight that in the case of PMs and ICDs the effects of electromagnetic interference are based on several physical factors such as the strength of the external signal, the distance between the PM or ICD signal, the frequency range, the type of modulation and the level of protection of the device. The effects of electromagnetic interference can be temporary or permanent malfunction such as inhibition, asynchronous or other faulty stimulation modes [24]. Furthermore, there are possible work-related effects like mechanical shock, dislocations, induction of currents with changes in threshold and device setting, incorrect detection, failure to perceive the rhythm.

For static magnetic fields (or quasi-static, up to a few Hz) it is recommended not to exceed the level of 1 mT except for short-term exposures, in order to prevent interference with AIMDs. The concept is explained in more detail in the EN 50527-1:2016 standard [32], which describes "transient exposure" as exposure to an EMF that is not continuous, foresees termination and/or reduction to non-influential levels and does not damage the implanted device. It must be determined by an acceptable response based on a recommendation from the cardiologist who performed the implant or, otherwise, included in the documentation accompanying the device. Regardless of how the risk assessment process is carried out, it must conclude with the identification of areas of free access (continuous or temporary) and areas of prohibited access to particularly sensitive workers, with a plan for adapting the workstation/activity.

EN 50527-1:2016 standard requires AIMDs to operate without interference up to the RLs for the general public, in accordance with Directive 1999/519/EC. Otherwise, it must be ensured that they have been manufactured in accordance with relevant cardiological guidelines. The risk assessment must therefore cover both EMFs above these levels in workplaces and also workers with AIMDs subject to lower immunity levels due to clinical reasons. EN 50499:2020 [33] standard identifies the equipment that should not produce EMFs above the RLs for general public. Further requirements for the assessment of exposure related to particular devices are included in some relevant standards such as EN 50527-2-1:2016 [38], specific for PM wearers.

Exposure in Workplaces

For chefs, a typical case is the use of induction cookers where food is heated by low-frequency magnetic fields (20 – 100 kHz) [39]. The procedure for assessing worker exposure is described in EN 50499:2020 [33]. It requires practical measurement of the magnetic field in the cook's common position for both intended and incorrect use. In research made by René Guldimann and Martin Meier [40], several factors were analyzed, including the total power supplied, the shape and size of the cooking plates, the centering of the pan on the plate, the distance of the edge of the table from the cooking surface and from the operator. In the worst-case scenario (P = 7 kW, 2 coils orthogonal to the operator, distances plate – table edge = 26 cm, hob – table edge = 18 cm and operator in contact with the table) the magnetic density flux was 56.5 μT, which increased to 65 μT in the case of an old pan with a loose bottom. At the involved frequencies the working RL corresponds to 1 mT, while that of the general public is 200 μT. However, compliance with the RLs may not be considered sufficiently protective for AIMD holders [41]. It would be advisable to refer to lower exposure limits, such as those set in the Italian legislation for a quality objective of 3 μT.

More generally, the main ELF sources are associated with the 50 Hz frequency, generated by overhead/underground power lines, transformer cabins or electrical machinery. They disperse EMF into the surrounding environment, e.g. under a 380 kV power line the electric field can exceed 5 kV/m and the magnetic induction a few tens of mT. Such intensities may concern, for example, power plants where, in typical worker's position a value of approximately 40 μT is estimated. Power distribution in a factory can lead to high magnetic induction levels at remote workplaces, connected to the electrical cabin by wiring. Significant exposure can be found in hand sanding processes (between 100 and 600 μT). Action value given for healthy workers by ICNIRP guidelines at 50 Hz is 1 mT [23].

In other industrial contexts, various types of electric furnaces are used for the melting and treatment of steel and other metals. The most significative are industrial heaters that produce the necessary temperature through radiofrequency or microwave EMFs. Other applications include soldering, hardening, tempering, melting, as well as use in the electronics field. Workers may be continuously exposed to magnetic induction between 100 μT and 10 mT with peaks above 100 mT.

Last but not least, if EMFs are not adequately shielded, they generate as an indirect side effect contact currents, which can cause shock and burn hazards, as well as damage to AIMD.

DISCUSSION

The first factor to take into consideration is whether the effects are direct or indirect, as the mechanisms involved in the cause-effect relationship are different. Indirect effects are attributed to the possibility of interference with AIMDs or other devices worn on the body, that can generate mechanical defects due to contact currents. Direct effects, on the other hand, are attributable to a stimulation of nervous structures, in particular neurosensory, and muscular structures that, at high frequencies, produce heating of organs and tissues. In this context appear subjective symptoms such as vertigo (sensation of instability), phosphenes, epilepsy, and disorders affecting the cardiovascular system. We believe that the main triggers of the arrhythmic "storm" in relational contexts are:

- Hydro-electrolytic or acid-base imbalance
- Hypoxia (exacerbation of heart failure, pulmonary embolism, lung infection)
- Hyperthyroidism
- Infection/fever
- Acute cardiac ischemia
- Poor compliance/abuse of cardioactive drugs
- Pro-arrhythmic effect of drugs
- Failure of left or right ventricular pacing.

In workplaces, the following factors are added:

- Increased ambient and radiant temperatures (e.g. heat from ovens and hot plates) which alter microclimatic conditions
- Gaseous chemical agents such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), generally irritants of the respiratory tract
- Viral/bacterial myocarditis
- Asthma
- Alveolitis caused by environmental fungi such as aspergilli and micropolyspora (split air conditioning)
- Magnetic fields generated by the operation of electrical equipment like microwave, radio frequency or magnetic induction ovens
- Stress factors.

For a worker with AIMDs, where a thorough experimental effort is required, the risk assessment process might involve modifying the job description or workplace [33]. For example, providing specific risk-free areas in which he can perform his work or, in extreme cases, prohibiting him from working. In pathologies similar to those just reported, this reasoning is not always exhaustive, having to distinguish between subjects free from cardiovascular pathologies, device wearers and patients who, in the presence of significant conductive anomalies, have not yet been treated with PMs.

Case I

For the cook who underwent ablation the best prevention of SCD in BrS was actually the use of ICD. This approach is especially true in patients who had a previous episode of cardiac arrest or syncopal event. ICDs do not prevent VF from occurring, but they react to defibrillate the episode, thus preventing SCD. The use of drugs e.g. quinidine – an antiarrhythmic drug with blocking activity of the Transient outward (Ito) and the Rapid component of the delayed rectifier (IKr) potassium currents [34-37] used in pharmacological treatment – had unwanted side effects (thrombocytopenia, intolerable diarrhoea, esophagitis, allergic reaction, worsening of sinus node dysfunction and the potential for QT interval prolongation and torsade de pointes). Furthermore, its availability was limited, especially in regions where BrS is endemic.

Case II

The metalworker was excluded from night shifts because they were contraindicated with the physiological variation of the sleep-wake rhythm. They were associated with molecular mechanisms of stress capable of interfering with cardiac function due to increase in 6/8 inflammatory cytokines and interleukins, bigger synthesis of adrenaline, metabolic alterations and increased reactive oxygen species [42]. The aim was both to prevent electrical instability and to ensure optimal maintenance of the functionality of ion channels for the repolarization of cardiomyocytes. In this way, the integrity of the conduction system in a subject with cardiac pathology was guaranteed in delicate cardio-functional balance as highlighted by the Electro-Physiological Study, considering the EMF linked to the functioning of machines with metal parts in continuous movement.

Case III

In the event of the electromechanics worker in the steel industry the preventive terms identification of activities and evaluations and the cancellation of interference with EMF appeared difficult. In this case, other associated risks had to be considered. Among these, high voltage, radiant temperatures, artificial optical radiation, manual handling of loads, biomechanical overload of the upper limbs, working at heights, inadequate postures, confined spaces, dust, fumes and gases indicated situations in which the accident event could occur unexpectedly and became seriously complicated. In this context, BrS type I emerged and, taking into account the familiarity for sudden death, the subject underwent dual-chamber Abbot-ICD implantation. The assessment of suitability for work involved limitations that determined incompatibility with the performance of various activities in the industrial plant. In fact, electromechanical maintenance work required intervention throughout the plant based on work shifts and contingent needs. Consequently, the role that could be performed required a different technological cycle and/or adaptation to other tasks as well as exemption from night work.

Diagnostic procedures are certainly recommended in all cases where there is a suspicious anamnesis or ECG. Therefore, in patients in whom the spontaneous type 1 pattern is not evident on the ECG, a 24-hour Holter ECG with modified leads is appropriate; if this is insufficient, a provocative pharmacological test with ajmaline should be performed. Echocardiography is useful to exclude other cardiac conditions and obtain a baseline assessment of general cardiac function. Differential diagnosis such as arrhythmogenic ventricular cardiomyopathy (ACM) and early repolarization are also important, and therefore collaboration with an experienced and passionate cardiologist is essential (45).

CONCLUSIONS

Brugada syndrome, whose affected subjects are considered particularly fragile, is actively studied both in genetic terms for the identification of direct sequencing of SCN5A from DNA, but also in electrophysiological and pharmacological terms. The evolution is however towards the exclusion or evidence of other cardiac disorders and conduction anomalies. It follows that the concerned subject presents also problems related to work commitments.

We have described some encountered cases with different characteristics that determine severity and subsequent complications, as well as possible improving solutions.

According to the guidelines (ESC / AHA / HRS), electromagnetic fields are not primary causes of arrhythmia and the danger arises from the interaction with triggering factors and not from occupational exposure, although the assessment is essential. The genotype, symptoms, e.g., fever, and drugs that affect the QT interval (LQTS) are important. There are no contraindications to MRI for carriers without devices.

In summary, Brugada syndrome is a quality control test for fitness for work, as the EMF risk assessment process cannot be ignored for affected individuals, both with and without implanted devices such as implantable cardioverter defibrillators (ICDs). Exposure to electromagnetic fields (EMF) raises concerns due to potential interference with devices, but also due to the sudden onset of arrhythmias. Preventive identification of the disease among personnel is essential.

It is generally accepted that ion channels, transmembrane proteins with primary, secondary, and tertiary structures that include charged radicals (electronegative or positive), can theoretically interact with electromagnetic (EM) or radiofrequency (RF) fields, but observed effects are generally minimal or absent at common environmental levels. Mutations have caused tissue-specific effects, with Purkinje cells showing more severe action potential prolongation than myocardial cells. Effects may occur at: high intensities (SAR >4 W/kg for RF, fields >100 μT for ELF), inducing oxidative stress or transient changes in gating, as seen in in vitro studies on Nav1.5. The voltage-gated sodium channel Nav1.5 has been implicated in the excitability of cardiac cells and in a variety of arrhythmic syndromes, including long QT, Brugada syndrome and conduction abnormalities. Further clarifications will certainly come from research sectors capable of clarifying the control mechanism and therefore the physiological role of the sodium channel in excitable cells (46). Some restrictions, such as the ban on working at heights, excessive exertion, heat stress, and night shifts, were adopted based on applicable criteria, taking into account situations of sustainable adaptation and combined risk to individual health, the environment, and the organization.How to perform risk stratification for asymptomatic Brugada ECG pattern. Modern research is moving towards an accurate control of functional sensitivity and a thorough diagnosis, which imply the use of new technologies and the knowledge of possible interactions, even in situations that currently exclude possible adverse events.

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