Spatial-varying Magnetic Field Evaluation during Activities in an NMR Laboratory

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Abstract: - Nuclear Magnetic Resonance (NMR) systems, vital in both academic and industrial labs, pose inherent risks from increasingly strong static magnetic fields, radiofrequency (RF) fields, and spatial magnetic field gradients. To address these electromagnetic hazards, the EU and ICNIRP have defined worker exposure limits. This research focused on assessing risks in a typical NMR lab, specifically for workers with Active Implantable Medical Devices (AIMDs). We precisely measured the static magnetic field around an 11.7 Tesla NMR spectrometer and computationally modeled the electric field induced in operators by their movements. Our analysis showed that all calculated exposure parameters were below legislative limits for acute occupational exposure. However, a critical finding was that the static magnetic field exposure exceeded the action level for AIMD wearers during tasks requiring close proximity to the spectrometer. This highlights a significant safety concern, demanding specific protocols for this vulnerable group.

Key-Words: - NMR safety, Magnetic Field measurements, Induced Electric Field, AIMDs, spatial-varying magnetic field, NMR workers exposure.

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1 Introduction

The fundamental principle behind the Magnetic Resonance (MR) technique relies on the action of three distinct magnetic fields: the primary static magnetic field, usually denoted as B0, which serves as the foundation for the phenomenon; the radio frequency field (RF), labeled B1, which is employed to perturb the nuclear spins and induce resonance; and the controlled magnetic field gradients applied along the three spatial dimensions (typically denoted as x, y, and z), which are crucial for spatially encoding the signals and precisely selecting the specific volume or area under investigation for analysis or imaging, [1], [2].

This technique is widely used in the medical field, finding application in both diagnostic procedures and within the realm of scientific research, and academic and industrial research for the analysis of a diverse array of sample types, ranging from mineral materials to organic substances, from biological systems to food products, [3], [4], [5].

Magnetic Resonance Imaging (MRI) does not use ionizing radiation, like X-rays and computed tomography (CT), the potential risks of using diagnostic MRI have always been a subject of debate and concern, [6], [7]. The reason for this concern is how MRI works and the electromagnetic fields it uses, [8], [9].

The main risks within the MR systems are represented by both the static magnetic field, which remains constant over time, and spatially heterogeneous magnetic fields, characterized by variations in strength across different locations. In some scenarios, exposure to RF fields also constitutes a potential hazard, [10], [11]. When workers move close to the magnet, they are also exposed to magnetic fields that change over time. These changing fields can create electric currents inside the human body. If these induced currents reach a sufficient strength, they can interact with the central nervous system (CNS), which may lead to various neurological effects, [12]. Moreover, these currents can also stimulate peripheral nerves, thereby eliciting sensory perceptions such as tingling sensations or involuntary muscle contractions. Several studies have highlighted transient physiological symptoms reported by workers who, for work reasons, moved near the magnet, [13], [14]. These temporary effects included sensations of dizziness and light-headedness, feelings of nausea, disturbances in visual perception, and the subjective experience of vertigo [15], [16], characterized by a sensation of spinning or imbalance, [17], [18], [19].

To address the aforementioned concerns regarding potential hazards associated with magnetic resonance environments, both the European Union (EU) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have established limits for the exposure of workers to the risks originating from physical agents, with a particular focus on electromagnetic fields (EMF) [20], [21]. These established limits aim to ensure a safe working environment for individuals operating within and around MR systems, [22], [23].

Worker exposure to static magnetic fields and the physiological effects resulting from movements within the spatially varying fringe fields surrounding MRI scanners have been the subject of considerable assessment and discussion, particularly for systems operating with field strengths ranging from 0.25 Tesla (T) up to 3.0 Tesla (T), which represent a common range for clinical diagnostic applications. These studies aim to characterize the potential risks associated with these magnetic field exposures for healthcare professionals and other personnel working in the vicinity of MRI equipment, [24], [25].

Nevertheless, despite our growing understanding of occupational hazards in clinical MRI settings, research specifically focused on occupational risk assessment for workers in NMR spectroscopy and, more broadly, in non-clinical magnetic resonance environments remains noticeably scarce, [26], [27]. These non-clinical settings encompass preclinical imaging facilities and fundamental research laboratories, where high-field magnets are routinely employed. These sophisticated analytical instruments are frequently utilized by "scientific users" rather than formally designated workers, [28]. Consequently, although these individuals may possess a high level of proficiency in the scientific applications and intricacies of the NMR technique, they often exhibit a limited awareness and understanding of the associated safety aspects and potential hazards, [29]. This lack of safety awareness can lead to a mistaken perception of Nuclear Magnetic Resonance (NMR) spectrometers as inherently low-risk devices, [30], [31]. Within this context, it becomes critically important and indeed essential to implement comprehensive educational initiatives aimed at informing all personnel, including these scientific users, about appropriate behavior, and the necessity of precise movement control within magnetic resonance environments to effectively prevent the occurrence of adverse events and ensure a safe working environment for everyone involved, [32], [33].

The aim of this study consists of "scientific users" occupational evaluation during routine activities conducted during probe positioning (in the upper side of the NMR) and matching and tuning of the signal working on the knobs located at the bottom of the spectrometer, [34], [35]. The comprehensive evaluation of worker exposure to the electromagnetic fields present in magnetic resonance environments, serving as a crucial component of the overall risk assessment process, is meticulously carried out by carefully considering and quantifying both the magnitude of the induced electric field, denoted as $|E|$, and the rate of change of the magnetic flux density over time, represented as $|dB/dt|$. These two parameters are of paramount importance in establishing and implementing safe working procedures and protocols within these environments, aiming to minimize potential risks to personnel, [36], [37].

Special emphasis and careful consideration are directed towards workers identified as being at particular risk within magnetic resonance environments. This category notably includes operators and personnel who have active implantable medical devices (AIMDs), such as pacemakers, implantable cardioverter-defibrillators (ICDs), or neurostimulators. This constitutes a particularly sensitive risk group that necessitates stringent protective measures to mitigate the potential for electromagnetic field interference, which could compromise the functionality and safety of their implanted devices, thereby posing significant health risks, [38], [39].

2 Problem Formulation

The static magnetic field of a NMR spectrometer was evaluated. The main characteristics of the spectrometer are reported in Table 1, while Figure 1 shows the room where NMR is positioned.

Table 1. Spectrometer properties

NMR	Bo (T)	Frequency (MHz)	Shielding
Varian	11.7	500	Active

The mapping of the static magnetic field was carried out using a three-axis Hall magnetometer HP-01 (Narda Safety Test Solutions Savona, Italy). The origin of the z-axis coincides with the ground while for the x-axis, the origin is fixed on the edge of the magnet. Negative coordinates on the x-axis indicate that positions are either above or below the scanner.

The magnetometer probe was positioned at the following heights: 50 cm, 70 cm, 100 cm, 130 cm, 163 cm, and 250 cm. We measured the modulus of the magnetic field |B| at each point by following the procedure below:

- Measurements were conducted at 100 cm intervals along the x-axis, from x = 450 cm to x = 50 cm, at the following heights: 100 cm, 130 cm, and 163 cm.
- Measurements were taken at 10 cm intervals along the x-axis, from x = 50 cm to x = 0 cm (the edge of the scanner NMR), at the following heights: 100 cm, 130 cm, and 163 cm.

In the range – 30 cm < x < 0 cm, the measurements were conducted at 10 cm intervals along the x-axis, at the following heights: 50 cm, 70 cm, and 250 cm.

The specific area under investigation for our measurements was the space situated between the NMR spectrometer and the operator console, both located within the same room. This particular zone is critical for assessing worker exposure, as it represents the typical workspace where operators interact with the device. To ensure the reliability and robustness of the obtained data, the aforementioned measurements of the static magnetic field within the NMR spectrometer environment were repeated three separate times.

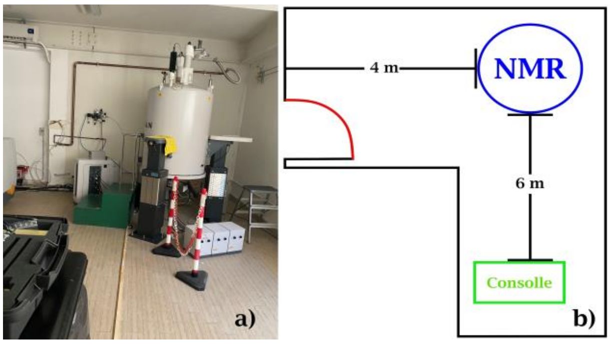

Fig. 1: NMR laboratory set up: (a) picture and (b) schematic visualization of the facility

This rigorous approach was undertaken to thoroughly check both the repeatability of the measurements, verifying the consistency of results obtained under similar conditions, and the reproducibility of the measurements, assessing the consistency of results across different measurement instances, thereby enhancing the overall validity and trustworthiness of the findings. From the acquired experimental measurements of the static magnetic field, the two-dimensional (2D) spatial distribution of the magnetic field strength on the vertical plane (specifically the xz plane) was computationally derived. This derivation was achieved by employing an exponential interpolation technique to fit the collected data points across the measurement area. The interpolation was performed on a finely defined grid with a spatial resolution of 1 × 1 centimeter, allowing for a detailed representation of the field distribution. All numerical calculations were computed by using a custom-developed script developed in MATLAB®, version R2022a (MathWorks, Inc., located in Natick, MA, USA). The modulus (absolute value) of the spatial gradient of the magnetic field strength, $|dB/ds|$, was calculated from the interpolation along both the x-axis and the z-axis. This computation of the spatial gradient provides information about the rate at which the magnetic field strength changes with position in these two dimensions. The ICNIRP guidelines [20], which are designed to limit human exposure to electric fields that are induced within the body as a consequence of movement through a static magnetic field, specify fundamental restrictions applicable in controlled conditions. These restrictions are expressed in terms of the strength of the motion-induced internal electric field, setting limits on the magnitude of these fields to prevent potential adverse health effects. The magnitude of the induced electric field, |E|, was estimated by employing the analytical model detailed within the ICNIRP guidelines, [22], [21]. This model is rooted in Faraday's law of induction, which establishes a direct relationship between the induced electric field and the temporal variation of the magnetic flux passing through a given area, in this case, a cross-section of the human body.

$$\oint_{\Gamma} \bar{E} \cdot d\bar{l} = -\frac{d\Phi_B}{dt} \qquad (1)$$

where:

- $d\Phi_B$ is the magnetic flux
- $\bar{E}$ is the electric field calculated over a path $\bar{l}$ on the surface Γ

Mathematically resolution of Faraday's law in our model considers the body cross-section as a circular loop with radius r oriented perpendicularly to the direction of the static magnetic field. Is possible to expand the circulation of the electric field considering the circular surface Γ:

$$\oint_{\Gamma} \bar{E} \cdot d\bar{l} = \oint_{\Gamma} E \cdot d\,l \cdot \cos(0) \;\Rightarrow$$
$$\Rightarrow E \oint_{\Gamma} d\,l = E 2\pi r = -\frac{\partial \pi r^2}{\partial t} \Rightarrow \qquad (2)$$
$$\Rightarrow E = \frac{r}{2}\frac{dB}{dt} = C\frac{dB}{dt}$$

Further expanding on this relationship and considering the scenario of a worker moving within a spatially varying static magnetic field, the induced electric field can be expressed in terms of the spatial gradient of the magnetic field and component of the velocity of the movement. Specifically, the relevant parameters are the time derivative of the magnetic flux density, |*dB/dt*|, the modulus of the spatial gradient of the static magnetic field, |*dB/ds*|, and the walking speed of the worker denoted as *v*. The exact mathematical form of the equation relating these quantities to E would typically be presented in the cited references [24], [40] and the ICNIRP guidelines [20], [22], [21]. |E| was calculated for the trajectory x using the analytical method proposed in the ICNIRP guidelines:

$$E = C\frac{dB}{dt} = C\left(\frac{\partial B}{\partial x}v_x + \frac{\partial B}{\partial y}v_y + \frac{\partial B}{\partial z}v_z\right) \qquad (3)$$

where:

- |*dB/dt*| is the time derivative of the magnetic flux density.
- *C* is a geometric multiplier depending on the size and shape of the body, as well as the direction and distribution of the magnetic field. In this study, we considered an elliptical section, from McRobbie et al. [40], with a = 0.4 m as the semi-major axial length and b = 0.2 m as the semi-minor axial. C = 0.16 $\mathrm{Vm^{-1}}$ per $\mathrm{Ts^{-1}}$.
- *∂B/∂x* represents the spatial gradient of the static magnetic field, calculated from the knowledge of the 2D distribution on the xz plane.
- *v* represents the worker's walking speed that was assumed constant during standard laboratory procedures. Based on the literature [24], [41], [42], the walking speed was set on values 1 m/s (normal activity around NMR) and 2 m/s (emergency activities around NMR the scanner).

Reference levels in terms of *dB/dt* are also established by the ICNIRP guidelines, [21]. Starting from equation 2 it is possible to verify the compliance of the reference level. All calculations were performed with a homemade MATLAB ®, R2022a (MathWorks, Inc., Natick, MA, USA) script. Results obtained in terms of |E| and *dB/dt* were compared with the ICNIRP exposure limits, [21].

3 Problem Solution

In Figure 2 we report the color map of the spatial distribution of the magnetic field gradient magnitude, *dB/ds*, within the area situated between the edge of the NMR spectrometer and console.

This map was generated based on calculations performed with respect to both the x-axis (horizontal direction) and the z-axis (vertical direction). The underlying magnetic field strength (|B|) measurements, which formed the basis for these gradient calculations, were acquired at the distinct heights above the ground plane: 100 cm, 130 cm, 80 cm, 120 cm, and 250 cm. This multi-height analysis provides a comprehensive understanding of how the magnetic field gradient varies both horizontally and vertically within the defined workspace.

In Figure 3 we report the color map of the spatial distribution of the magnetic field gradient magnitude, *dB/ds*, within the area situated under the NMR spectrometer, in particular from the edge of the spectrometer and its center.

Figure 4 shows the modulus of the magnetic flux density |B| (in mT) along the linear trajectory on the x-axis between x=260 cm and NMR spectrometer (x=-30 cm) at the chosen six heights respect the ground (z=50 cm, z=70 cm, z=100 cm, z=130 cm, z=160 cm, z=250cm). The action level (AL) to limit the interference with the function of active implantable medical devices (AIMDs) at 0.5 mT, specified by regulations [17], [19], is also shown, along with the AL of 3 mT which is set to limit the projectile risk in the fringe field from strong sources (>100 mT).

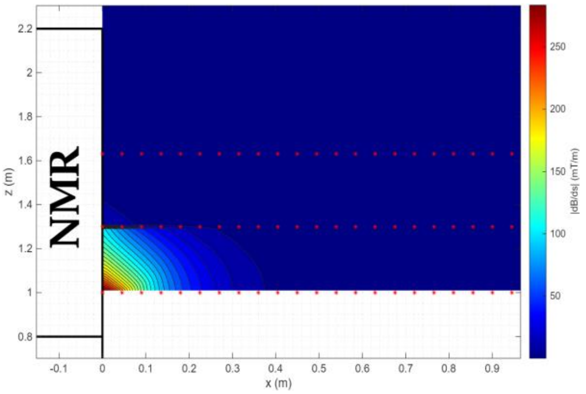

Fig. 2: Spatial gradient from the edge of the NMR spectrometer towards the console |dB|. Red stars indicate heights of measurement of |B|

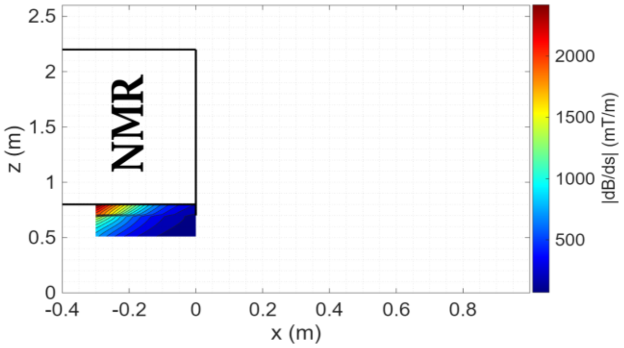

Fig. 3: Spatial gradient from the center of NMR to the edge | dB |. Red stars indicate heights of measurement of |B|

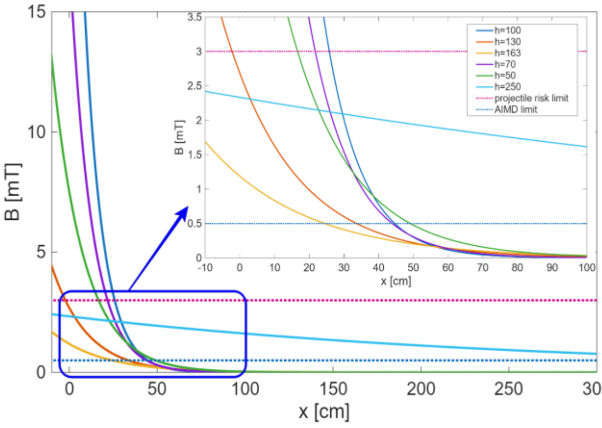

Fig. 4: Modulus of the magnetic flux density |B| (in mT) along the linear trajectory on the x-axis between x=260 cm and NMR spectrometer at the chosen six heights respect the ground

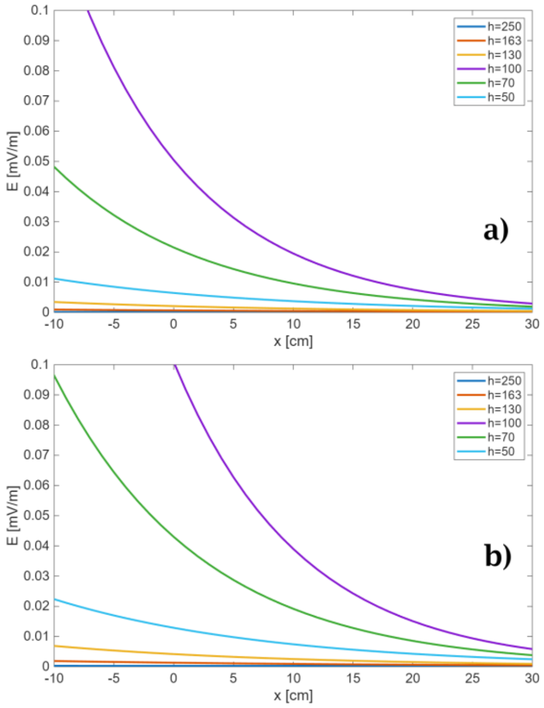

Fig. 5: Calculated induced electric field |E| on the body of a worker walking along a linear trajectory on the x-axis at constant velocity: (a) *v* = 1 m/s; (b) *v* = 2 m/s. x = 0 corresponds to the edge of the scanner

Observing the graph, it is evident that the level of exposure exceeded the AL of AIMDs in these points: (x=51cm, z=50cm), (x=46cm, z=100cm), (x=45cm, z=70cm), (x=34cm, z=130cm), (x=25cm, z=163cm). At a height of 250 cm, this limit is exceeded already by 270 cm.

In terms of AL of projectile risk, this is exceeded at x=38 cm for z=100 cm, at x=29 for z=70 cm, and x=25 cm for z=50 cm. Height z=250 cm never exceeds this limit while the others only surpass it inside the spectrometer.

Figure 5(a) illustrates the calculated induced electric field, |E| (expressed in mV/m), within a worker's body. This calculation assumes the worker is moving along a straight path on the x-axis at a constant velocity of *v* = 1 m/s. The figure visually represents how the electric field is induced under these specific conditions. Figure 5(b) shows the calculated induced electric field |E| referred to a worker moving at a constant velocity *v* = 2 m/s.

Table 2 and Table 3 show the peak value of the calculated parameters |*B*|, |*E*| and |*dB/dt*| for each z-height for the two different movement scenarios v_1 = 1 m/s and v_2 = 2 m/s, corresponding to a normal and emergency scenario, respectively.

Table 2. Peak values of the calculated exposure parameters for individual heights for the worker moving at $v = 1$ m/s

Peak value	**z=50 cm**	**z=70 cm**	**z=100 cm**	**z=130 cm**	**z=1630 cm**	**z=250 cm**
|B| (mT)	39.22	195.14	601.98	2.68	11.98	3.42
|E| (mV/m)	0.067	0.242	0.873	0.009	0.001	0.000
|dB/dt| (mT/s)	1.513	1.513	5.457	0.055	0.012	0.001

Table 3. Peak values of the calculated exposure parameters for individual heights for the worker moving at $v = 2$ m/s

Peak value	**z=50 cm**	**z=70 cm**	**z=100 cm**	**z=130 cm**	**z=1630 cm**	**z=250 cm**
$\|B\|$ (mT)	39.22	195.14	601.98	2.68	11.98	3.42
$\|E\|$ (mV/m)	0.337	0.484	1.746	0.019	0.004	0.001
$\|dB/dt\|$ (mT/s)	3.026	3.026	10.915	0.117	0.024	0.002

4 Conclusion

The scientific literature regarding occupational exposure within NMR environments is notably limited and lacks comprehensive detail [43], [44], particularly when juxtaposed with the extensive research dedicated to characterizing professional exposure for healthcare personnel who routinely work with MRI scanners in clinical settings, [37], [45].

Regarding chronic occupational exposure to static magnetic fields (SMFs), the available body of epidemiological and experimental evidence has been considered limited in scope and often insufficient in methodological rigor to permit the derivation of definitive and universally accepted conclusions regarding potential long-term adverse health effects in exposed workers, [46], [47].

To thoroughly investigate and characterize the levels of occupational exposure to the magnetic fields produced by an NMR spectrometer operating at 11 Tesla (T), this study presented a computational tool specifically designed to estimate the electric field induced within a human operator's body as a consequence of their movements within the static magnetic field. As anticipated, the collected and analyzed data unequivocally revealed that the highest magnetic field strength levels, correspondingly indicating the greatest potential exposure values for personnel, were consistently recorded near the NMR spectrometer itself, where the static magnetic field is most intense. This proves how important it is to have solid safety protocols and to make people aware of the risks when they're around this kind of high-field equipment. None of the calculated exposure parameters exceeded the relative limits reported by legislation, [21].

On the other hand, an NMR environment can pose specific risks and complications for workers with certain types of implanted and other medical devices. These risks primarily arise due to a complex interplay of factors, most notably the interactions between the magnetic field generated by the NMR system and the sensitive electronic components of these devices. A particularly unique and significant concern associated with introducing an AIMD into the MR environment is the inherent potential for device malfunction. Exposure to static and spatial-varying electromagnetic fields can induce undesirable currents or interfere with the delicate electronic circuitry within the AIMD, potentially leading to various adverse device behaviors. These malfunctions can manifest as a gradual degradation of performance, a complete loss of the intended therapeutic function of the device, or even the occurrence of unintended and potentially harmful responses, thereby posing direct risks to the health and well-being of the individual with the implant.

Observing Figure 4, it is possible to notice that the AL limit for AIMDs is exceeded at less than 0.5 meters from the spectrometer. From Table 2 and Table 3, we can observe how none of the peak values exceed the limits imposed by the regulations for controlled exposure, [21]. A proportional increase in |E| and |dB/dt| for each z-height is associated with a double speed, which leads to increased exposure of workers moving around the spectrometer under emergency conditions.

In this study, we conducted a comprehensive evaluation of the safety aspects associated with a specific NMR spectrometer for personnel engaged in their typical routine work activities within its operational environment. Our analysis of the measured exposure levels indicated that, across all evaluated scenarios, the exposure of both the whole body and the limbs of the workers to the generated magnetic fields remained below the established limits stipulated by the European Directive concerning protection against the short-term health effects resulting from acute occupational exposure to electromagnetic fields. However, our study revealed a critical observation: at approximately 1 meter from the external surface of the spectrometer, employees were exposed to a static magnetic field with a strength exceeding 0.5 mT. This value is particularly significant as it represents the established threshold limit for workers who have AIMDs, highlighting a potential safety concern for this specific subgroup of workers.

It's important to underline that NMR technology is constantly evolving, and the spectrometers are getting higher static magnetic field intensities. This trend significantly increases the risk for staff working near these devices. For this reason, we need to be more aware and use much stricter safety protocols. Our approach, which computes the induced electric fields inside the workers as they move around, holds significant potential for evaluating occupational exposure in the context of long-term neurobehavioral effects. This approach can contribute valuable data for future epidemiological studies, useful to establish evidence-based safety guidelines for long-term occupational health in this research field.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors wrote, reviewed and edited the content as needed and verifies that none utilised artificial intelligence (AI) tools were used. The authors take full responsibility for the content of the publication.

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Conflict of Interest

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