Antoni CIEŚLA, Przemysław SYREK

AGH Akademia Górniczo-Hutnicza w Krakowie, Katedra Elektrotechniki i Elektroenergetyki

Parameters and position of the applicator's effect on magnetic field distribution during magnetotherapy

***Abstract**. This paper presents the results and method of optimization the elliptical applicator used in the magnetotherapy of fractures. Eight parameters describing the structure and position of the applicator have been adopted. The authors discuss three variants of the fitness function and the reasons for choosing one of them. Due to the complicated boundaries of feasible solutions, the fitness function is increased by the value returned by the penalty function for all the individuals. The article also describes the influence of selected parameters on the behavior of the fitness function in the neighborhood of the point optimal is presented.*

***Streszczenie.** W artykule przedstawiono metodę i wyniki optymalizacji aplikatora eliptycznego, wykorzystywanego w magnetoterapii złamań. Przyjęto osiem parametrów opisujących budowę i położenie aplikatora, omówiono trzy warianty funkcji celu wraz z uzasadnieniem wyboru jednej z nich. Ze względu na skomplikowane granice zbioru rozwiązań dopuszczalnych, do oceny osobników dołączono odpowiednią funkcję kary. Przedstawiono wpływ wybranych parametrów na zachowanie funkcji celu w otoczeniu punktu optymalnego. (**Wpływ parametrów i położenia aplikatora na rozkład pola magnetycznego podczas magnetoterapii**).*

Keywords: magnetic field, magnetotherapy, genetic algorithms, cardiac pacemaker.
Słowa kluczowe: pole magnetyczne, magnetoterapia, algorytmy genetyczne, rozrusznik serca.

Introduction

Magnetotherapy has been included and recognized as one of the many ways to treat a wide range of diseases. Although it was discovered many years ago [1,2], the interest in the world of science was achieved by finding that pharmacology was at the limit of obtaining significant progress. In individual cases, magnetotherapy is the only remedy that could be applied, for example, if the patient is not allowed to receive additional doses of drugs. There is no doubt that progress in this branch of medicine is possible thanks to technology. Providing properly prepared equipment and correct, and simultaneously, secure use of it, requires also numerical calculations that illustrate the physical quantities, relevant from a therapeutic point of view. The most important of the quantities are the intensity of the magnetic field and current density induced in treated anatomical structures. In this paper the authors present the methodology for selecting the location of the applicator in relation to an anatomical structure, evaluate the impact of the position of the applicator on the distribution of magnetic induction at the orthopedic injury while maintaining a safe level of induction at the location of the pacemaker.

Applicator's assessment methodology

The choice of appropriate parameters of the applicator – providing the fit values of the magnetic field – is important in the case of many diseases, including fractures. To analyze the impact of the applicator's shape and position relative to the selected portion of the body on the treatment, as an example, the distal end of the humerus has been selected. Within the distal end of the humerus, there are several components. It is estimated that approximately 40% of fractures of the humerus are fractures of the distal end, as they are common injuries of the elbow area [3]. View of the upper limb model with highlighted distal end of the humerus is shown in figure 1.

In this article the authors discuss several ways to evaluate the distribution of the magnetic field induced by the applicator during the magnetotherapy and select an appropriate fitness function, which is used to optimize the construction of the applicator. A simplification has been applied: the magnetic field resulting from the flow of eddy currents in the time variable magnetic field induced by the applicator has been omitted.

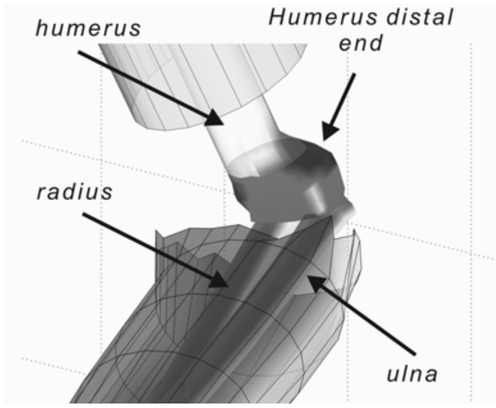


Fig.1. Part of an upper limb (left), with the spotlight of the humerus distal end

Applicator's parameters and position

The problem of assessing the impact of the position of devices on the treatment, with a suitably selected fitness function is given in [4], while the construction of the device, in [5]. To describe an elliptical coil, independent variables, which correspond to both its construction and its position in three dimensional space are used.

It was assumed that the magnetic field induced by the current flow in the coil is a sine wave, and the value of the root mean square of the module of magnetic induction is calculated for the current in the coil applicator with a RMS value either below or equal to 10 A. The conductor cross-section is assumed to be 0.75 mm^2 (hence the results received from the current safety margin, which at that section of the pipe located in the plaster is 15 A). It is assumed that the wires are wound with such a distance that their cross-section centers are placed with offset of 2 mm.

To estimate the parameters and position of the applicator, and the nature of the magnetic field distribution, the authors propose the so-called an elliptical applicator. For a full description of such applicator windings, it is necessary to adopt three parameters - independent variables (figure 2), which are necessary to generate the parametric curve [6], used to calculate the magnetic field in the space surrounding the applicator.

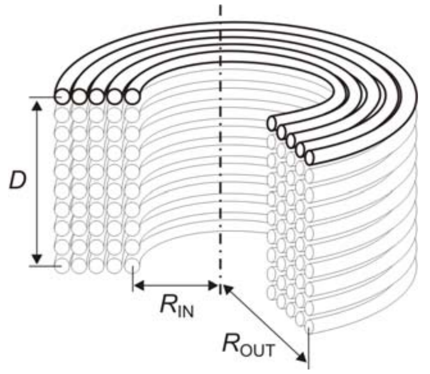


Fig.2. An elliptical applicator with optimized parameters

The curve depicting winding of the applicator is described by parametric curves and can be transformed: rotated to any angle and moved in space (fig. 3), which corresponds to the location of the applicator relative to any orthopedic injury.

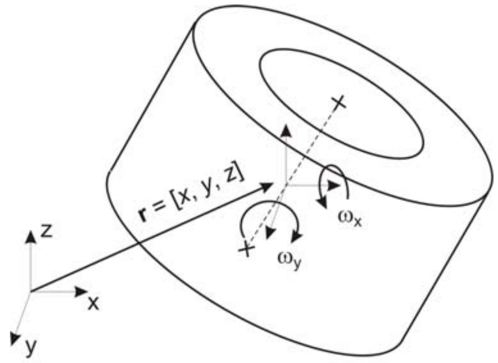


Fig.3. An elliptical applicator and its parameters describing the position in space, that are to be optimized

Thus, the optimum point (when made and adopted restrictions on how the assessment) is given by means of eight independent variables:

$$\overline{x}_{\mathrm{i}} = \{R_{\mathrm{IN}}, R_{\mathrm{OUT}}, D, \omega_{\mathrm{X}}, \omega_{\mathrm{Y}}, x, y, z\} \tag{1}$$

after encoding, the parameters presented above form the genotype, which is used to evaluate the individuals. The solution is obtained in two steps: by using genetic algorithm and by using local optimization methods (gradient descent method) to the "best" individual.

Selection of fitness function

In order to carry out the optimization, it is necessary to specify how the individuals in the generated population are evaluated. The authors considered three options. Two of them will be discussed briefly, and based on the last of them (the third) the optimization of the applicator is run.

As the first way to measure of magnetic field distribution in the magnetotherapy, the following parameter is adopted:

$$\lambda = \frac{|\mathbf{B}_{\max}|}{|\mathbf{B}_{\min}|} \tag{2}$$

where: $|\mathbf{B}_{\max}|$ – maximal value of the magnetic field module within selected area (here: distal end of the humerus), $|\mathbf{B}_{\min}|$ – respectively: minimal value (within the same area).

λ parameter, being the ratio of above presented values, has to be minimized. Minimizing causes that the distribution of the magnetic field induction in the designated area takes similar values, which leads to providing a specific magnetic field in the desired area. The effect of adopting such a fitness function, is locating the applicator far away from the upper limb, more precisely – on the border of the feasible solution for the parameters responsible for the location of the applicator. Consequently, the magnetic field on the damaged part of the bone reaches very low values, which involves two defects of such a solution. Firstly, it is necessary to narrow the set of feasible solutions so that the winding of the applicator was big enough to be able to obtain the appropriate value of the field - it increases the construction costs, and increased energy consumption by using an applicator (in the case of fractures, applied magnetic field reaches up to 100 mT [7]). Secondly, placing of the applicator away from arm contributes to exposing the other parts of the patient's body to the impact of the field of larger values than in the fracture site [8] .

The second criterion used to determine the fitness function value can be the mass of an applicator - omitting housing - proportional to the length of the winding, combined with the condition of reaching the intended minimum value of the field in the selected area. This assumption means that the applicator is located as close as possible to the fracture, which eliminates the problem of the field that affecting the whole body of the patient. The disadvantage, however, is uneven field distribution in the damaged portion of the body.

The authors propose to adapt such a function to avoid conducting multi-criteria optimization, which results in the need for the weighted sum of vector components of the performance index and matching the appropriate weight. Due to the requirements of magnetotherapy, feasible solutions is correspondingly narrowed.

Therefore, the objective function is selected, as described in the next section.

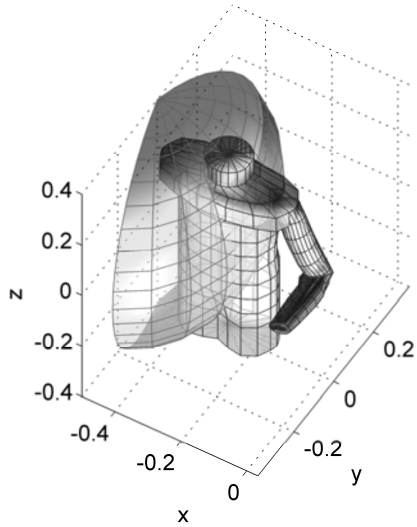
Protection of patients with pacemakers

In [9-13], it was pointed out that in a magnetic field with a frequency of 50 Hz and induction above 100 μT may lead to interference with a pacemaker, due to, inter alia, the possibility of activating the circuit responsible for the reprogramming of the pacemaker, equipped with reed relay [14]. Both passive shielding and active shielding methods are effective in the frequency band used in magnetotherapy [15], yet they result in additional costs. Due to the increasing number of patients who use pacemakers, and at the same time suffer from orthopedic injuries, the possibility of using magnetic field therapy in these cases should be considered.

The fitness function is constructed in such a way as to determine both the parameters of the applicator and its position to minimize the magnetic field in the vicinity of pacemaker (assuming that it is located near the left shoulder) and maximized in the damaged area (in this case the distal end of the humerus). Thus, the quality index is as follows:

$$\lambda = \frac{|\mathbf{B}_{\mathrm{pm}}|}{|\mathbf{B}_{\mathrm{b}}|} \tag{3}$$

where: $|\mathbf{B}_{\mathrm{pm}}|$ – maximal value of the magnetic field module within the protected area (surrounding of the pacemaker localization, figure 4), $|\mathbf{B}_{\mathrm{b}}|$ – minimal value of the magnetic field module within selected area (within the distal end of the humerus, figure 1).



Rys.4. Torso and left arm model, with the surface separating the pacemaker localization

Figure 4 presents a model of the patient torso, with the intersecting surface. On this surface, the set of control points is generated (a few tens), to calculate value of magnetic field. $\left|\mathbf{B}_{\mathrm{pm}}\right|$ value (formula 3) is maximal level of magnetic field within this set. $\left|\mathbf{B}_{\mathrm{b}}\right|$ value, In turn, is a minimal value obtained within the set of control points within the cured area (highlighted on figure 1). The shortest distance from distal end of humerus to so called control surface is equal to 0.32 m.

Feasible solutions and fitness function restrictions

Within the problem of optimization it is assumed that the area of feasible solutions is a hypercube. Since the torso and the left hand of the patient model have been removed from the feasible area, a method of penalty function is applied. The fitness function is increased by the external penalty function [16], whose value is proportional to the number of control points generated on the surface of the applicator (figure 5), situated outside the permissible area, within the patient's torso or arm.

Also limitation related to the value of the magnetic field on the surface separating the pacemaker has been imposed. It is assumed that with the maximum permissible value of the current powering applicator, the maximum value of the magnetic field on the surface has to be as high as at least 100 μT. Thus, the lower limit will cause that the applicator obtained in the optimization process reaches such proportions that will generate the most realizable value of the magnetic field in the treated area. Without this condition, the applicator with a minimized value of fitness function (equal to 0.0052), has such small dimensions and short coil (0.38 m, at the cross-section of 0.75 mm^2 of Cu-wires, translates into a mass equal to 2.55 g winding), the value of induction on the surface separating the pacemaker is only 0.3 μT, and the minimum value in the area treated with 57.7 μT.

The results show that the minimization of the objective function without further restriction is not sufficient. Hence, the fitness function is increased by a second penalty function, proportional to the difference that exists between the boundary value of 100 μT and value achieved on the separating surface.

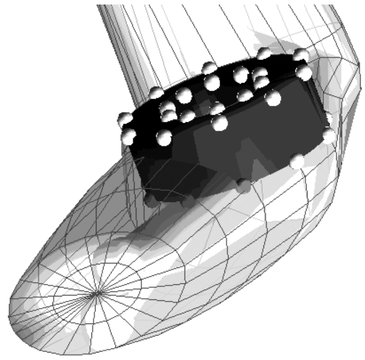


Fig.5. Model of the left arm, with the control points marked on the surface of the applicator, which are outside the acceptable area (inside hand)

In the genetic algorithm, individuals that do not meet the above restrictions are tolerated by the first half of the empirically adopted number of generations, and after crossing the adopted number of generation so called the death penalty is used, and individuals do not meet the restrictions are eliminated. The death penalty is also used in local optimization, which is used to winning an individual (the gradient descent method).

Obtained results

Optimizing the parameters resulted in the applicator for which the fitness function reaches 0.0266. Successive values of the independent variables are – coil length: 50.3 m; mass: 0.337 kg; R_{IN}: 0.031 m; R_{OUT}: 0.053 m; D: 0.032, ω_X: 96.7°, ω_Y: 58.6°, [x, y, z] = [0.0149, 0.0525, -0.0024]. With suitably chosen current powering applicator, so that the maximum value of the magnetic field within the surface separating the pacemaker was exactly 100 μT, the minimum value of the magnetic field in the area of distal end of the humerus is 3.75 mT.

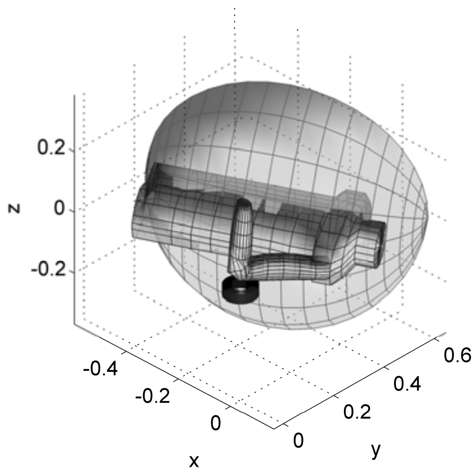


Fig.6. Applicator placed to the origin

Before attempting to assess the impact of selected parameters on the behavior of the fitness function value in the neighborhood of the optimal point, transformation was made, consisting of rotating the applicator and model of the torso and left hand so that all independent variables describing the position of the applicator had a value of 0 (figure 6).

Both moving the applicator along the z-axis (in the positive direction, fig.7), as well as reducing their thickness (fig. 8), lead to a lower value of the fitness function. Introduced results presents that the optimal point is located on the border of the feasible solution. In the first case a further reduction of the fitness function value is limited by the location of the patient's body, and in the second case, the inability of the applicator to generate a magnetic field of sufficiently high induction.

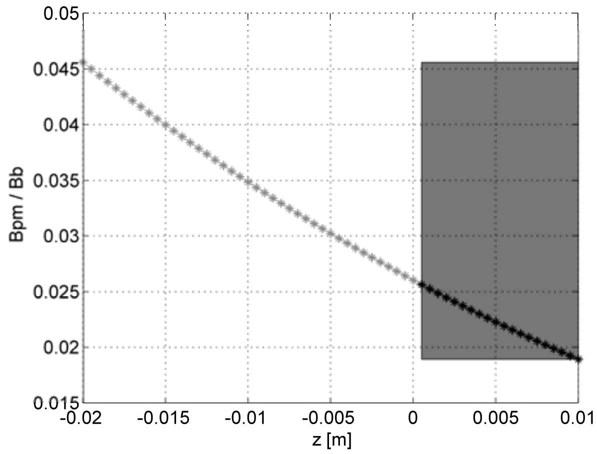


Fig.7. Fitness value as a function of applicator position along the *z*-axis (filled rectangle contains points outside the set of feasible solutions)

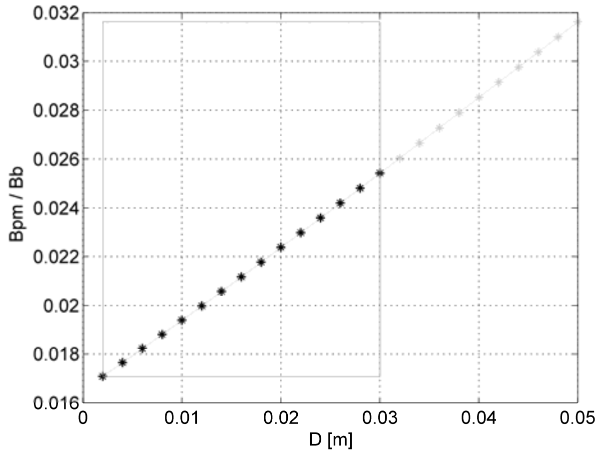


Fig.8. Fitness value as a function of applicator height – *D* parameter (filled rectangle contains points outside the set of feasible solutions)

Conclusions

The presented results of the evaluation of an elliptical applicator parameters and its position, should point to two important issues. First, patients with implanted pacemakers are not pre-excluded from the group of people that can use magnetotherapy (even if it is not possible to insert a screen between the treated area and the place of the pacemaker implantation). The second issue that the authors want to emphasize is, the position of the applicator relative to the damaged anatomical structure. In our case, intuition suggests that the applicator should be placed as close to the elbow, and as far away from the zone separating the location of the pacemaker. Location obtained numerically puts the applicator, in extension of the ulna, so in place closer to the control zone, than the left hand side. It is therefore suggested that numerical optimization, can create the possibility to use, satisfactory values of magnetic field levels satisfactory from the medical point of view (of the order of several militesla), even without the use of shielding.

REFERENCES

[1] Krawczyk A., Łada-Tondyra E.: Pierwsze próby stymulacji magnetycznej – historia odkryć dwóch uczonych, Przegląd Elektrotechniczny, 86 (2010), n.12, 202-205
[2] Cieśla A., Kraszewski W., Tadeusiewicz R.: Visualization of magnetic field generated by portable coil designed for magnetotherapy, Przegląd Elektrotechniczny, 88 (2012), n.10a, 127-131
[3] Ceynowa M., Sobierajska A., Biegański S., Bieniecki M., Lorczyński A.: Odlegle efekty leczenia złamań dalszego odcinka kości ramiennej u dzieci, Annales Academiae Medicae Gedanensis, 36 (2006), 21-32
[4] Starzyński J., Szmurło R., Kijanowski J., Dawidowicz B., Sawicki B., Wincenciak S.: Distributed Evolutionary Algorithm for Optimization in Electromagnetics, IEEE Transactions on Magnetics, 4 (2006), 42, 1243-1246
[5] Hsiung Hsu K., Durand D.M.: A 3-D Differential Coil Design for Localized Magnetic Stimulation, IEEE Transactions on Biomedical Engineering, 10 (2001), 48, 1162-1168
[6] Cieśla A., Syrek P.: Parametric curves in the specification of windings of applicators used in magnetotherapy, Przegląd Elektrotechniczny, 88 (2012), n.9a, 213-216
[7] Krawczyk A., Miaskowski A., Ishihara Y., Łada-Tondyra E.: Healing of orthopaedic diseases by means of electromagnetic field,, Przegląd Elektrotechniczny, 86 (2010), n.12, 72-74
[8] Cieśla A., Kraszewski W., Skowron M., Syrek P.: Determination of safety zones in the context of the magnetic field impact on the surrounding during magnetic therapy, Przegląd Elektrotechniczny, 87 (2011), n.7, 79-82
[9] Krawczyk A., Pławiak-Mowna A., Miaskowski A.: Badania kardioimplantów w polu elektromagnetycznym w środowisku pracy, Przegląd Elektrotechniczny, 81 (2005), n.12, 28-30
[10] Trigano A., Blandeau O., Souques M., Gernez J.P., Magne I.: Clinical study of interference with cardiac pacemakers by a magnetic field at power frequencies, J Am Coll Cardiol., 2005, 15; 45(6), 896-900
[11] Karpowicz J., Gryz K., Zradziński P.: Pola magnetyczne przy urządzeniach do magnetoterapii – ocena ryzyka zawodowego, Bezpieczeństwo Pracy, 9(2008), 21-25
[12] American Conference of Governmental Industrial Hygienists (ACGIH) – Threshold Limit Values for Chemical Substances and Physical Agents. Biological Exposure Indices. 2007
[13] Dawson T.W., Caputa K., Stuchly M.A.,Shepard R.B., Kavet R., Sastre A.: Pacemaker Interference by Magnetic Fields at Power Line Frequencies, IEEE Transactions on Biomedical Engineering, 49(3), 2002, 254-262
[14] Augello A., Della Chiara G., Mariani Primiani V., Moglie F.: Immunity Tests of Implantable Cardiac Pacemaker Against CW and Pulsed ELF Fields: Experimental and Numerical Results, IEEE Transactions on Electromagnetic Compatibility, 3 (2006), 48, 502-515
[15] Caminiti, I. M. V.; Formisano, A.; Lupoli, M. C.; Martone, R.; A new approach to design flexible magnetic active shielding, IEEE Transactions on Magnetics, vol.PP, no.99, 1-5
[16] Arabas J.: Wykłady z algorytmów ewolucyjnych, Wydawnictwa Naukowo-Techniczne, Warszawa, 2001

Authors: *dr hab. inż. Antoni Cieśla (prof.nz.AGH), dr inż. Przemysław Syrek, AGH Akademia Górniczo-Hutnicza w Krakowie, Katedra Elektrotechniki i Elektroenergetyki, al. Mickiewicza 30, 30-059 Kraków, E-mail: aciesla@agh.edu.pl; syrekp@agh.edu.p*