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Visualization of magnetic field generated by portable coil designed for magnetotherapy

***Abstract**. The evolution of medicine and technological development allow to create new devices applied in magnetotherapy, which open up new possibilities of diseases' treatment. Especially it might be interesting to create a device for magnetotherapy, which can be used at home. To meet this expectation new portable devices producing the desired field as well as small-sized coils applicators are newly developed. Moreover, development of software used to control process of field production (using computer devices) allows the patient to a far-reaching self-service after programming the time scheme of stimulation previously done by professional and experienced therapist. In this last task the visualization of field penetration through the limb may be very helpful. It will allow to match proper shape of the applicator with the type of disease being treated, and the shape and size of the damaged area of the body and help the patient to understand essence and course of treatment.*

***Streszczenie.** Rozwój medycyny i postęp technologiczny pozwalają na opracowanie nowych urządzeń wykorzystywanych w magnetoterapii. Stwarza to nowe możliwości leczenia. Szczególnie interesujące wydaje się stworzenie urządzeń do magnetoterapii, które mogą być stosowane w warunkach domowych. Sprzyjają temu nowoopracowane przenośne urządzenia wytwarzające potrzebne pola oraz małogabarytowe cewki aplikatorów. Z kolei rozwój oprogramowania używanego do sterowania (za pomocą urządzeń komputerowych) procesem wytwarzania pola pozwala pacjentowi na daleko idącą samoobsługę po uprzednim zaprogramowaniu schematu czasowego stymulacji przez fachowego i doświadczonego terapeutę. W tym ostatnim zadaniu bardzo przydatna będzie przedstawiona w tym artykule wizualizacja wnikania pola do kończyny. Pozwoli ona dobrać kształt aplikatora do rodzaju leczonej choroby oraz do kształtu i wymiarów uszkodzonego miejsca ciała a także pomoże pacjentowi w zrozumieniu istoty i przebiegu terapii. (**Wizualizacja pola magnetycznego wytworzonego przez przenośną cewkę przeznaczoną do magnetoterapii**).*

Keywords: magnetotherapy, low frequency magnetic field, computer simulations.
Słowa kluczowe: magnetoterapia, wolnozmienne pole magnetyczne, symulacje komputerowe.

Introduction

The influence of electromagnetic field on living organisms has been of interest to scientists for centuries [1, 2]. The results of experiments reveal that the low-frequency electromagnetic fields, magnetic fields in particular, may have various impacts biophysical [3], some may be significant on the health of living organisms. This statement broadens and supplements the medical paradigm about living organisms as "chemical reactors". Various processes take place there, and they can be observed by determining concentrations of chemical substances in tissues (e.g. biochemical analyses of blood or other systemic fluids samples) and regulated by adding various substances. As a consequence, the diseases have been commonly treated by administering chemical substances (pharmacological treatment), the number of which is dangerously increasing now. Recent investigations revealed that apart from the biochemical functional models of human organism, the advantages of which are undisputable, it is also a biophysical model which can be successfully involved. In the latter case the disease is treated as a disturbance of biophysical processes typical of well-being.

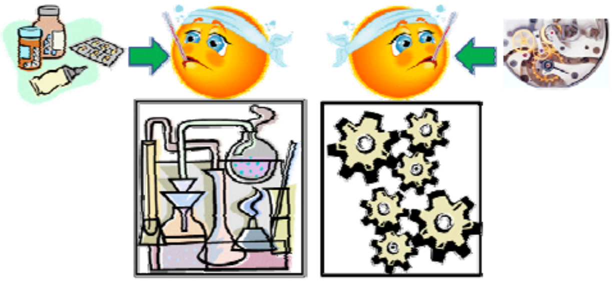

Fig.1. Machine as a healing factor, analogous to pharmacological treatment (description in the text)

This paradigm assumes that, besides pharmacological means, the disease can be also treated with physical factors supplementing and regulating natural biophysical processes. In such an approach it is purposeful to use the physical reaction as an element of treatment, with a technical device as a healing tool which is also responsible for the proper application of the physical factor. Briefly speaking, a machine becomes a healing agent when the organism is also conceived as a machine, analogous to a situation when a pill or injection are healing factors when the organism is treated as some kind of chemical reactor (Fig. 1).

There are a lot of physical factors which are used for treating diseases, but the authors of the paper will focus only on magnetic field, which may produce a variety of possible impacts and which creates theoretically unlimited therapeutic options [2] of using electromagnetic field on living organisms [3]. The use of magnetic field for medicine belongs to the most intensely developing directions of interdisciplinary cooperation between doctors, engineers and physicists, thus providing a dynamic development of this branch of biomedical engineering and medicine.

Magnetic field for medicine

When talking about the biological effects of different physical factors, especially those that are invisible to our senses as well as difficult to mental understand and control by amateur - the first reaction of people is fear. To allay these fears (or confirm) carried out various scientific studies, which the results met with great popular interest. The result of such research was the investigations on the negative influence of electromagnetic fields on flora, fauna and humans are on-going. Simultaneously however, has revealed a positive impact of these fields on living beings, so scientists started to analyze possibilities of employing them on behalf of a man. One of the first scientific communications about medical applications of electromagnetic fields was a work by A. von Sarbo on „Clinical analyses of therapeutic value of electromagnetism in treating diseases”. This work was published in 1905. Then followed years of multidirectional investigations of the influence of magnetic fields on living organisms [3], with special emphasis on low-frequency magnetic fields.

The researches on the therapeutic effect of low-frequency magnetic fields cover various experiments: from submolecular mechanisms analyses to laboratory experiments on animals. However, the clinical experiments turned out to be most dynamic. The therapeutic use of low-frequency magnetic fields stays within the domain of the so-called physical medicine, which depending on the physical parameters of the field, splits into two subdomains, i.e. magnetotherapy and magnetostimulation. The former, i.e. magnetotherapy is addressed in this paper.

Magnetotherapy

Magnetotherapy is a method of treating diseases with low frequency magnetic field. The ions in the body cells get displaced under the influence of magnetic field, causing (as observed) hyperpolarization of cell membrane. These biophysical phenomena reinforce the metabolism in cells and tissues, mainly during energy processes taking place there. This also enhances inter alia, the use of oxygen by the cell. These metabolic changes may help the treatment of various diseases, including bone fractures, hard to heal wounds, burns, inflammation, etc.

According to the criteria generally accepted in physical medicine, the frequency of magnetic fields used in magnetotherapy is lower than 100 Hz whereas the magnetic induction is 0.1 to 20 mT. These values are two to three orders higher than the terrestrial magnetic induction, and 3 orders lower than magnetic induction used in medicine for MRI - so according to current medical knowledge definitely safe. The most frequently applied courses of fields are sinusoid, triangular, rectangular, as well as their half courses [3].

Numerous investigations [4, 5, 6] revealing the effect of variable magnetic fields on living organisms became basis for using variable magnetic fields in medicine for treating some diseases. The recently developing biomedical engineering, electronics and medical electrical engineering created new possibilities for using electromagnetic fields in a number of clinical disciplines [4]. Presently, the low-frequency magnetic field is used for treating the following diseases and disorders:

a) diseases of kinetic system (post-traumatic states, pseudarthrosis, osteoporosis, degenerative joint disease and inflammation of joints),

b) diseases of nervous system (states after cerebral stroke, migrene),

c) skin and soft tissue diseases (burns, crural ulceration, bacterial infections of skin and soft tissues, decubitus ulcer, unhealing wounds).

Above mentioned diseases do not close the list magnetotherapy applications, though these are most frequent cases, documented with clinical analyses [5, 7].

Apparatus used in magnetotherapy

Professional devices applied in magnetotherapy, e.g. Magnetronic MF-10 (most frequently encountered in consultation rooms) make use of low-frequency impulse magnetic field.

Depending on the type of treatment, the applicators are fed with regulated frequency current (1 Hz to 50 Hz) and of various courses (full sinusoid, triangular, rectangular, or their half courses), and the induction level does not exceed 20 mT [8]. An example of a typical large-size applicator has been viewed in Fig. 2.

Also assessed the range of safety zones described in the labor laws of different types of applicators [11]. Recently many manufacturers of magnetotherapy equipment appeared on the market.

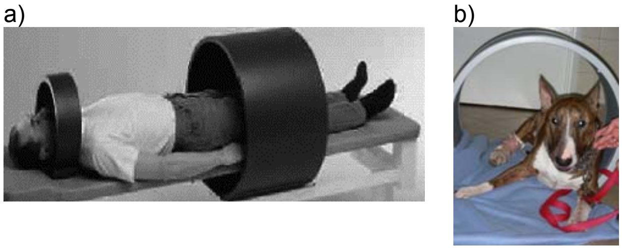

Fig. 2. Large-size applicators a) for humans [9], b) for animals [10]

They offer modifications and improvements of apparatuses with applicators. They try to create the most universal product with the widest spectrum of applications. Hence a question of whether all such apparatuses meet the requirements set by therapists, whether or not the parameters and magnetic field values are the same as given in the scientific literature in reference to a specific disease. This issue needs further studies, analyses and the introduction of a system of verification and certification. This paper is not focused on ready-made devices for magnetotherapy, but the present results of the simulation results of work equipment created at the Institute of Electrical Engineering [12].

Small-size applicator

A simple small-size coil which can be used both in hospitals and also by patients at home has been presented in Fig. 3. Thanks to the used material and change of shape of winding this applicator can be better adjusted to the stimulated part of the body in such a way that only the treated part is stimulated. With this type of applicator the magnetic stimulation is applied precisely to the place which is to receive the magnetic field (according to recommend the doctor).

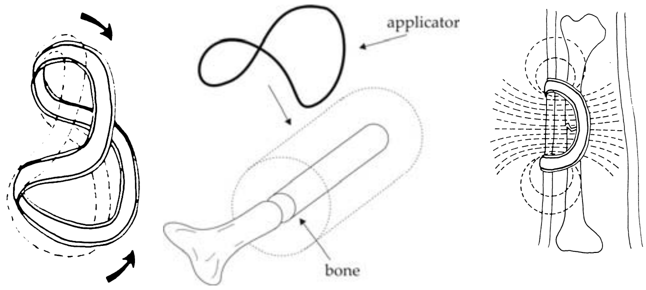

Fig. 3. Small-size applicator [12, 13], operation of which is the subject of simulation presented in

An important element of this work is the modeling and visualization of magnetic fields generated by presented applicator. In this way the magnetic induction inside the applicator and inside the treated organ can be accurately defined. Thanks to the adjustability of the shape of the applicator's coil to specific needs, the magnetic induction in the treated part of the body will be definitely closer to the value set up by the doctor than in the case of large-size applicators. Moreover, the magnetic field of the proposed coil is not so dispersed as in the case of commonly used applicators. In this way the group of patients who could profit from the therapeutic influence of magnetic field could be increased. This applies e.g. those patients with heart pacemakers, who normally external magnetic fields must be avoided. Another advantage of this type of applicators is the simplicity of use also by the patients (of course, after prior instructed by the doctor).

It can be also added that magnetic field is applicable not only to rehabilitating people but also for animals (Fig. 2 b). The presented approach lies in adjusting the applicator to the shape of the magnetically-treated part of the body. This option solves the problem of staying motionless (which is the case in large-size applicators), and making treating animals much easier and comfortable.

Mathematical model

For making a good use of advantages offered by the proposed small-size applicator it seems purposeful to work out its mathematical model, and to visualize the magnetic field generated in the analyzed organ. Authors express their hope that the computer techniques employed to magnetic field imaging will result in more precise localization and better adjusting of the applicator to the medicinal needs. This is especially important when the device is applied by patient himself. In the case of clinical magnetotherapy the correct therapeutic use of magnetic field can be guaranteed by experienced medical personnel and the applicators themselves. In case self-spatial by patient, modeling of the field and easily interpretable graphical visualization of the result of modeling play a very important role. It is worth observing that such a visualization of the magnetic field will also help design applicators of various shapes and parameters which will be applicable to magnetotherapy but not only.

For the set up shape of the applicator the vector potential should be calculated at point for each line section, then the potentials at all segments should be summed up and the field calculated at point as a rotation of vector potential. The vector magnetic potential was defined as follows [14]:

(1) $$\mathbf{A}(\mathbf{r}) = \frac{\mu I}{4\pi} \oint \frac{d\mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|}$$

(2) $$\mathbf{B}(\mathbf{r}) = rot\,\mathbf{A}(\mathbf{r})$$

The vector potential was presented as a sum of elementary vectors from *K*-segments, into which the coil was divided.

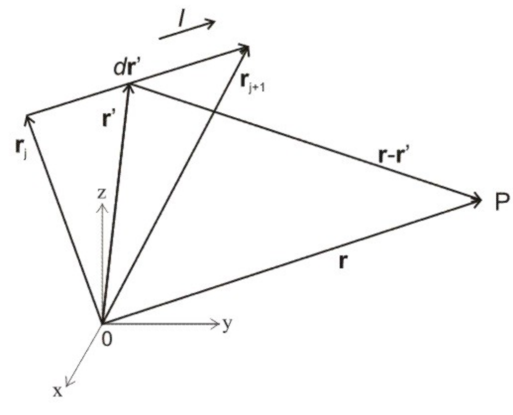

Fig. 4. Geometrical interpretation to the equation (1)

Equation (1) assumes the following form:

(3) $$\mathbf{A} \approx \mathbf{A}_K = \frac{\mu I}{4\pi} \sum_{j=1}^{K} \int_{\mathbf{r}_j}^{\mathbf{r}_{j+1}} \frac{d\mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|}$$

with the additional condition, that:

$$\mathbf{r}_{K+1} = \mathbf{r}_1$$

The leading vector **r'** of current element *I*d**r'** at section $\overline{\mathbf{r}_j \mathbf{r}_{j+1}}$ and infinitely small displacement *d***r'** along section $\overline{\mathbf{r}_j \mathbf{r}_{j+1}}$, have been described with equations:

(4) $$\mathbf{r}' = \mathbf{r}_j + (\mathbf{r}_{j+1} - \mathbf{r}_j)t', \qquad 0 \le t' < 1$$
$$d\mathbf{r}' = (\mathbf{r}_{j+1} - \mathbf{r}_j)dt'$$

where, parameter *t'* is used for interpolating section $\overline{\mathbf{r}_j \mathbf{r}_{j+1}}$. Therefore, the integral in equation (3) assumes the form:

(5) $$\int_{\mathbf{r}_j}^{\mathbf{r}_{j+1}} \frac{d\mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|} = \int_0^1 \left(\frac{d\mathbf{r}'}{dt'}\right) \frac{dt'}{|\mathbf{r} - \mathbf{r}'|} = = (\mathbf{r}_{j+1} - \mathbf{r}_j) \int_0^1 \frac{dt'}{|\mathbf{r} - \mathbf{r}'|}$$

where the distance between the current element *I*d**r'** and distant point *P* is given with the formula:

(6) $$|\mathbf{r} - \mathbf{r}'| \equiv \sqrt{\begin{aligned} &\{x - [x_j + (x_{j+1} - x_j)t']\}^2 + \\ &+ \{y - [y_j + (y_{j+1} - y_j)t']\}^2 + \\ &+ \{z - [z_j + (z_{j+1} - z_j)t']\}^2 \end{aligned}}$$

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$$\mathbf{r} = [x, y, z]$$
$$\mathbf{r}_{j+1} = [x_{j+1}, y_{j+1}, z_{j+1}]$$
$$\mathbf{r}_{j+1} = [x_{j+1}, y_{j+1}, z_{j+1}]$$

where j = 1,…,K.

After solving the above equations the rotation operator should be applied to obtain the magnetic induction vector at point *P*.

(7) $$\mathbf{B} \approx \mathbf{B}_K = rot\mathbf{A}_K$$

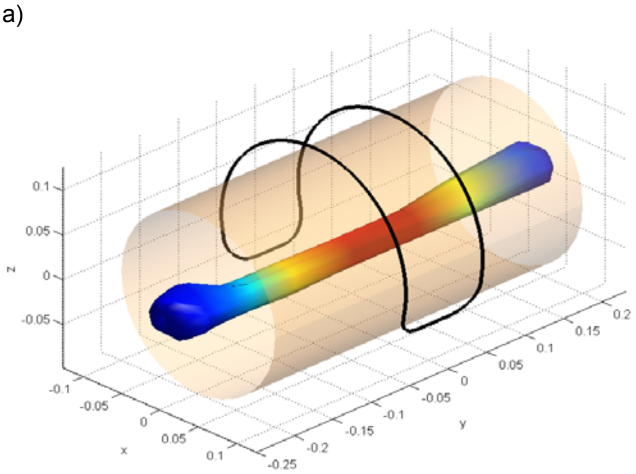
Simulation results

The above equations were used to build the program, in which an exemplary distribution of induction module of magnetic field on the bone surface has been presented in Fig. 5 a and b. The parameters of the applicators should be so selected that the distribution of magnetic field strength in the place of the fracture was equal over the entire surrounding - of course equal to that, the doctor will determine the optimal in therapeutic point of view. The presented results of simulation have a qualitative character. This allows for the evaluation of the influence of the shape and parameters of the applicator on the magnetic field distribution. The size of the coil depends on the size of the treated limb and type of disorder.

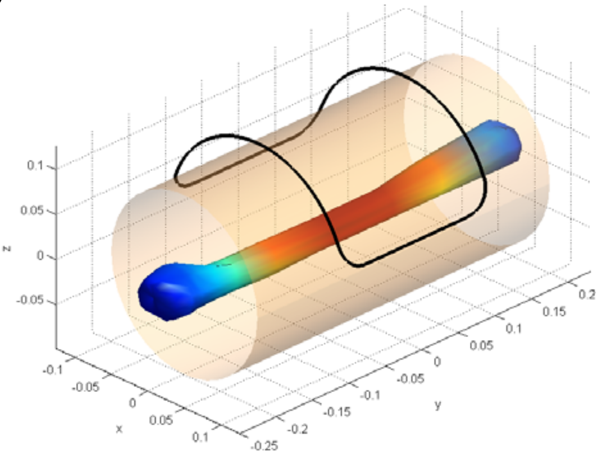
If the limb was broken in the middle of its length, both the first and the second way of administering the applicator (Fig. 5. a and b) will bring about expected therapeutic results. The induction of magnetic field covers damaged places and visibly concentrates the magnetic field in the place of fracture. Figure 5b shows the same applicator, the same but in different ways fit. This type of arrangement will bring more effective therapeutic effect of the broken leg in several places at once.

The presented mathematical model was implemented in the Matlab software environment.

a)



b)



c)

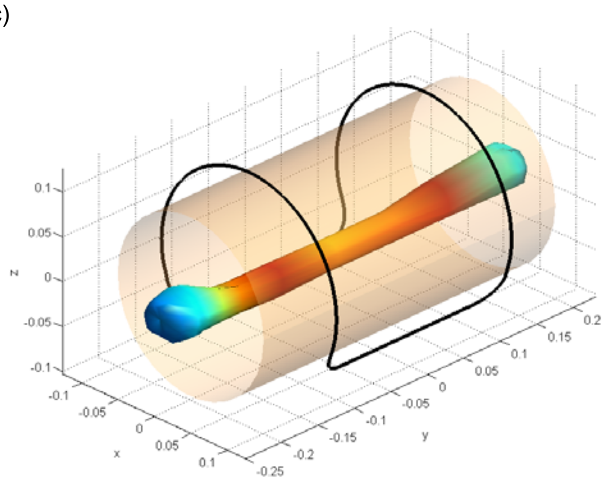
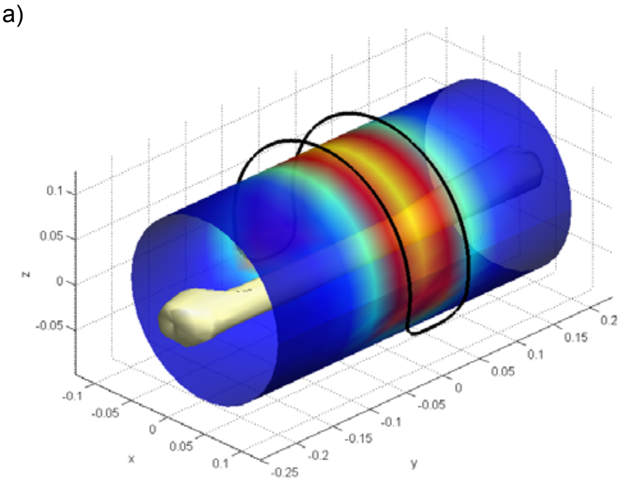


Fig. 5. Distribution of magnetic field induction on bone for: a) single fracture in the middle of the limb, b) composite fracture of a limb, c) misadjusted size of applicator

However, Figure 5c illustrates the effects of incorrectly matched applicator size to disorder - can be seen that the maximum induction field is not obtained at the fracture, only in the regions closer to the distal bone and the proximal end.

Magnetotherapy is used not only to fractures but also for treating wounds, burns, skin problems, etc. The required field distribution in such a case, it should provide high intensity on the body surface, and a small value inside.

a)



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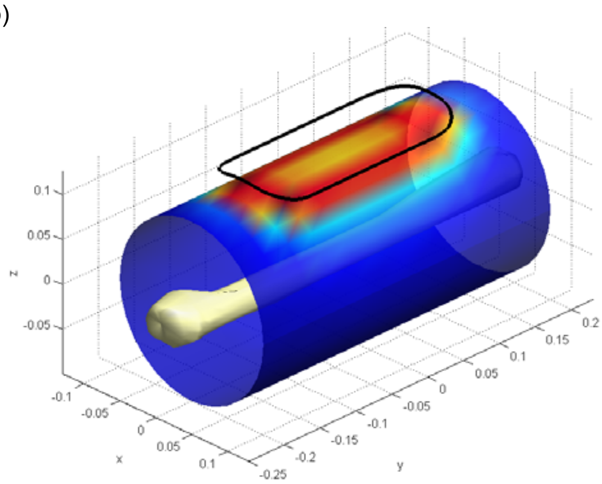

c)

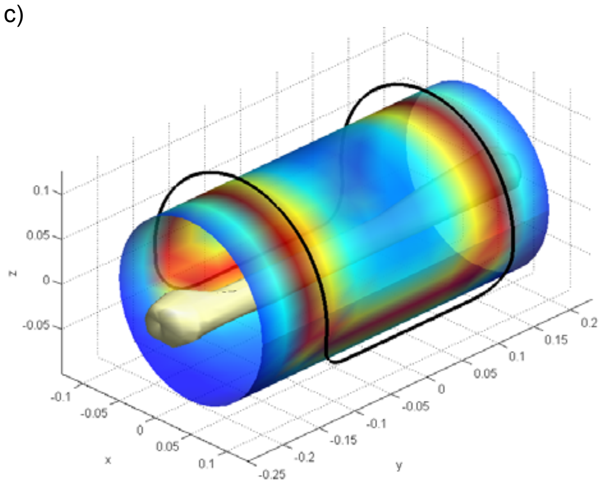

Fig. 6. Distribution of magnetic field induction on skin surface for: a) hard to heal wounds around the limb, b) local disorder, c) incorrectly selected the shape of the applicator to the disorder

Figure 6 illustrates the distribution of magnetic field on the skin surface. The shape of the applicator is selected depending on the place, size and radius of the skin problem (Fig. 6 a and b).

In figure 6c shows an example of the simulation, when the magnetic field does not reach to the disorder located in the middle of the leg, because was selected incorrect size of the applicator. Improperly sized coil shape (with the same parameters of the field) causes it impossible to obtain the desired therapeutic effect using magneto therapy.

Concluding remarks

The therapeutic effect of low-frequency magnetic field on human and animal organisms has been proved by numerous studies and experiments performed for years. Knowing (not discussed in detail here of biophysical and clinical observations) desired therapeutic parameters of the magnetic field (frequency, shape, strength, length of pulse, exposure time) one can design a new apparatus with applicators, which would meet technical requirements and, before all, expectations of the patients and their therapists. Bearing in mind the medically justified length of magnetotherapy it is purposeful to concentrate on its home uses. This however needs a tool supporting the patient in the process of self-servicing in the magnetotherapy application. Such an instrument is proposed in this article.

Created and described in this work a mathematical model of the magnetic field, with the tools to visualize the field distribution, will allow for numerical simulations needed for this type of support. On the basis of the calculations and their visualization the doctor would be able to precisely select parameters of applicators and could accurately determine the fragment of the limb to be stimulated. Magnetic field generated by small-size applicators will concentrate in the diseased place also when applying the applicator will perform a patient not having the required knowledge or practice in the use of.

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