Physical Analysis of Pulse Low-Dynamic Magnetic Field Applied in Physiotherapy

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Abstract

This article makes an effort to explain some physical and energy aspects of practice using magneto therapy in the treatment of the musculoskeletal system (orthopaedic surgery, physiotherapy and the rehabilitation). We are presenting the principles of electromagnetic induction in muscle tissue as typical example of the parts of human body. The main accent of presenting theory is put on macroscopic physical behaviour of low-frequency electromagnetic field in living body parts. The problems are indicated with modelling. This approach use simplified model of tissue conductivity. One of the goals is to warn about different distribution of magnetic field in parts of body caused by different position, spatial orientation and metal implants too. The each metal part implanted into human body has strongly influence on distribution physical effects into. Another analyse introduces physical and energy differences among individual types of power sources of magnetic field and their dynamic behaviour.

Keywords

Magneto therapy
Electromagnetic induction in living tissue
Metal implants

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1 Introduction

Every living creatures by own activities produce electromagnetic field. Does external low frequency magnetic field have influence on living structure?

1.1 Medical Aspects

This "historical" magnet therapy, magnetic therapy, or magneto therapy, based on the use of the static magnetic fields is considered by most of the doctors' pseudoscientific alternative medicine practice.

Pulsed electromagnetic field therapy (PEMFT), also known as *pulsed magnetic field therapy (PMFT)* or *low field magnetic stimulation (LFMS)*, was introduced as a therapeutic method in many areas of medicine at the end last century and especially during last decade and it is considered as an effective procedure especially for the treatment of the musculoskeletal disorders (orthopedic surgery, physiotherapy and the rehabilitation) [1, 2].

Clinical experience has shown that pulsed electromagnetic field therapy may be used for a number of conditions and issues, and that the benefits include:

- Reduction of pain and inflammation
- Improve energy/circulation, blood/tissue oxygenation
- Regulate blood pressure and cholesterol levels as well as the uptake of nutrients [3, 4]
- Increase cellular detoxification and the ability to regenerate cells
- Accelerates repair of bone and soft tissue/relaxes muscles, [4] etc.

Many theories about the healing principles of the pulsed electromagnetic field on the living human tissue were published, but no of them has brought the clear explanation, so

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many doctors don't accept this method as an "evidence based medicine" procedure [3, 5].

PEMFT is considered very safe method. There are no contraindications to PEMFT except in cases of haemorrhage or where electrical implants are in use. In contrast to chemical medicaments, there is no over dosage, at least within the field range that are presently used for treatments. The PMF therapy is a heatless therapy, therefore, all implants (except heart pacemakers) can be treated. Fractures can be treated even through a plaster cast, since magnetic fields permeate all materials. Its advantages are relatively low cost and simple use. It does not require any skilled operator. Furthermore, in order to get the maximum efficiency of the method, its basic principle and important parameters should be known.

Table 1 The characteristic conductivity of representative tissues. Electromagnetic properties of tissues in frequency range up to 1 MHz

Conductivity	γ_t [S/m]
Blood	1.23
Cartilage	1
Muscle along	0.43
Muscle across	0.17
Porous bone	0.17
Subcutaneous fat	0.057
Brain Grey Matter (average)	0.23
Brain Grey Matter—according to direction	0.19–0.25
Metal Implants: Stainless steel	1.1×10^6
Titanium	1.8×10^6

1.2 Theoretical Premises

The fundamental description of magnetic effects on living organism is described in many articles and books [1]. These texts, particularly medical literature, very often present the studies in different physical units. The electromagnetic field is completely described by four Maxwell equations [6]. This theory is appropriate to description of inner electromagnetic field in human bodies and in the tissues. The tissues and human and animal bodies mainly consist of diamagnetic substances. The magnetic fields penetrate through all parts of the body without difficulty and external magnetic field strength $\mathbf{H_m}$ is slightly attenuated. The fractional reduction of the magnetic field in living tissue is caused by a variation of electron orbits of atoms or molecules and it is less than 10 millionths from range. The frequency of external magnetic field is low and therefore dielectric losses are not taken into account too therefore the following table (Table 1) presents conductivity of selected typical tissues only [7]. The examples of tissue conductivity show that human or animal body is strongly heterogeneous surrounding from electromagnetic view. We can speculate about low intensity of external electromagnetic field so the conductivity of individual tissue is linear.

The ones of tissues (particularly muscle and brain) are anisotropic. The magnetic field direction has substantial influence on physical effect in each point tissue.

For unified description it is very important to present the definition of physical notions and units in International System of Units (SI), (Table 2) e.g. [6, 7].

1.3 Energy or Power Balance in Tissue

The variable external magnetic field is transformed into the strength of electric field $\mathbf{E_t}$ in tissue. According to Ohm's law the strength of electric field produces current density $\mathbf{J}$ because the tissue is adequately conductive γ_t, e.g. [1, 6, 8]. The product of electric field strength $\mathbf{E}$ and current density $\mathbf{J}$ indicates power density w_t which is absorbed in tissue. We suppose that external magnetic field is low frequency and therefore dielectric losses are not taken into account [7].

One of the important parameter how to define the effect of variable magnetic field in tissue is electric field strength $\mathbf{E}_t$ (see Eq. 1).

Medical literature defines this biophysical effect with the current density in tissue $\mathbf{J}_t$ [A/m^2] or [A/cm^2], 1[A/m^2] correspond to 100 [μA/cm^2] or 0.1 [mA/cm^2] (3). This parameter is significant for statement of non-hazardous levels of magnetic field e.g. [9–13]. The local current density in the tissue we can describe as follows (2, 3):

$$\mathrm{E_t} = \left(\frac{\mu}{\gamma_t}\mathbf{H}_m \frac{\partial \mathbf{H}_m}{\partial t}\right)^{\frac{1}{2}} \tag{1}$$

$$\mathrm{J_t} = \left(\mu\gamma_t\mathbf{H}_m \frac{\partial \mathbf{H}_m}{\partial t}\right)^{\frac{1}{2}} \tag{2}$$

The important parameter how to evaluate the impact of external magnetic field is energy density absorbed in tissue. This situation is presented by the following Eq. (4). The density of energy in tissue w_t (see Eq. 5) is a local parameter valid for actual time intervals and space in the part of body.

The variable external magnetic field is transformed into the strength of electric field $\mathbf{E_t}$ in tissue. The product of electric field strength $\mathbf{E_t}$ and current density $\mathbf{J_t}$ indicates power density w_t which is absorbed in tissue. This follows from 2nd Maxwell Equation or Faraday's Induction law. According to Ohm's law the strength of electric field produces current density $\mathbf{J_t}$ because the tissue is adequately conductive γ_t, e.g. [6].

$$\boldsymbol{J}_t = \gamma_t\, \boldsymbol{E}_t \tag{3}$$

Table 2 Determination of Physical Units

γ_t—conductivity of tissue	[S/m], [m^{-3} $kg^{-1}s^3A^2$]
$\mathbf{J}_t$—current density in the tissue	[A/m^{-2}]
$\mathbf{E}_t$—electric field strength in the tissue	[V/m], [$m.kg.s^{-3}A$]
w_m—density of magnetic energy coming into tissue	[J/m^3], [m^{-1} kg. s^{-2}]
$\mathbf{H}_m$—external magnetic field strength	[A/m]
w_t—density of energy absorbed by tissue	[J/m^3], [m^{-1} kg. s^{-2}]
$\mathbf{B}_m$—external magnetic induction in tissue	[T], [$kg.s^{-2}A^{-1}$]
W_m—total magnetic energy coming into tissue	[J]
$P_{m\ \max}$—top of magnetic power coming into tissue	[W]
p_t—density of power absorbed by tissue	[W/m^3]

Table 3 The circuit parameters of magneto therapy coil

Inner Inductance	L = 0.05	[H]
DC resistance	R_{DC} = 15	[Ω]
Number of turns	n = 335	
Winding length	l = 340	[mm]
Ellipse axis	600 × 560	[mm]

$$w_t = \int_{t_1}^{t_2} \boldsymbol{J}_t \cdot \boldsymbol{E}_t dt = \gamma_t \int_{t_1}^{t_2} E_t^2\, dt = \frac{1}{\gamma_t} \int_{t_1}^{t_2} J_t^2\, dt \tag{4}$$

$$\mathrm{w_t} = \mu \int_{t_1}^{t_2} \boldsymbol{H}_m \frac{\partial \boldsymbol{H}_m}{\partial t} \mathrm{dt} = \frac{1}{2} \mu \left[\mathrm{H_m^2}\right]_{t_1}^{t_2} \tag{5}$$

$$\mathrm{W_t} = \int \mathrm{w_t dV} \tag{6}$$

We expect that this power-producing parameter would be more important for evaluation of magnetic field efficiency. It is evident that impact of magnetic field depends on the content of tissue which is inserted into the space of operating external field. This situation is described by Eqs. (7, 8).

$$\mathrm{P_t} = \int \mathrm{p_t dV} \tag{7}$$

$$\mathrm{P_t} = \int_V \boldsymbol{J}_t \cdot \boldsymbol{E}_t\, \mathrm{dV} = \frac{\mathrm{d}}{\mathrm{dt}} \int_V \mathrm{w_m dV} \tag{8}$$

$$\mathrm{W_t} = \iiint_V \mathrm{w_t dxdydz} \tag{9}$$

This relation represents the total energy loss and it is given by cubic integral (7), e.g. [7, 8]. Other way how to define impact of magnetic field into human body is expression of instantaneous power. This situation is described by Eq. (8).

The Eqs. (7, 8) is derived from the integral representation of energy conversion principle which is presented in Eq. (1). The Eq. (2) is transformed by this way.

2 Limitations of Magneto Therapy Using

Physiotherapy use several types and sizes of magnetic applicators for application of magneto therapy. These magnetic adapters can be classified as the applicators with open or closed magnetic circuit. Comparatively great cylindrical coil are very popular in medical offices that is why we chose these types for our experiments. These coils do not include ferromagnetic core and the magnetic field is continuous.

2.1 Sources of Magnetic Field

This presented type of magnetic applicator is the biggest which is used in magneto therapy and rehabilitation care. The large profile along with relatively short length of open air coil does not allow creating inside sufficient large space of homogenous magnetic field. The magnetic applicator (according to Fig. 1) is open air coil without ferromagnetic pole extension. The design of device is frameless and therefore the profile of coil is slightly ellipsoidal.

In this case the maximum current in coil (Fig. 1) is chosen 2 A. The distribution of magnetic induction is shown in the Fig. 2.

Violet curve shows distribution along *x* axis on periphery of the coil and red curve is according x axis in centre. The simulation verifies our assumption that the lowest intensity of field is right in the point of intersection between axis *y* and axis *z* in the center. The level of magnetic induction **B** can range in units [mT]. In comparison with induction of geomagnetic field ($\mathbf{B}_{geomg}$ ~ 30 ÷ 50 [μT]) this application of magneto therapy used more than hundredfold more powerful magnetic induction, [6].

2.2 Influence of Location and Orientation in Magnetic Field

In our simulation is used simple model of leg which is placed off-center (Fig. 3). This approximation is imperative to indicating energy effects in the model of leg. The position

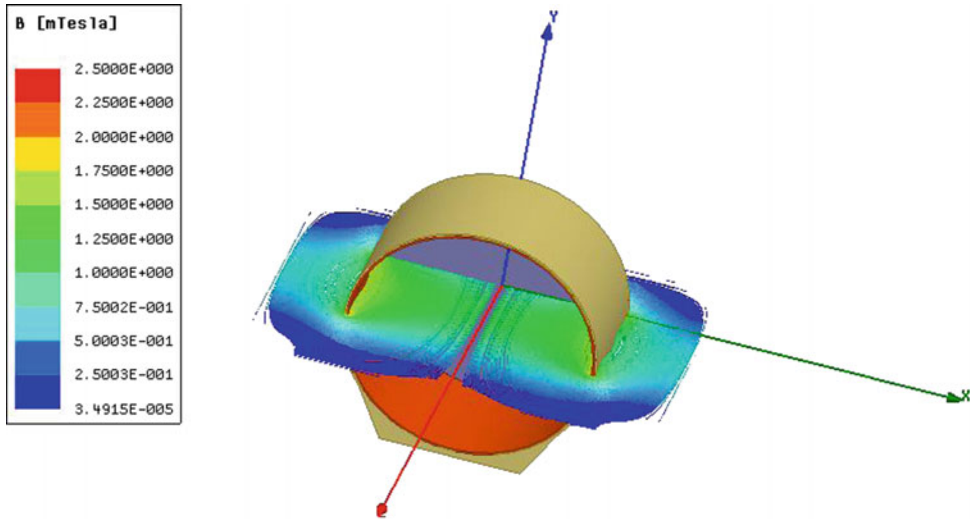

Fig. 1 Magnetic field of elliptic magnetic coil (Table 3)

of treated body part in the center of coil is not optimal for therapy but we can see this positioning in medical praxis very often. Low-frequency magneto therapy uses particular sequences of rectangular voltage pulses generated on input of a coil. For this reason the simulation is implemented on one pulse of therapeutic sequence only.

Low-frequency magneto therapy uses particular sequences of rectangular voltage pulses generated on input of a coil. For this reason the simulation is implemented on only one pulse of therapeutic sequence.

Magnetic field is driven by current of the coil only. The Fig. 4 presents waveform, one of representative current pulse (red line). The energy effect in tissue is realised only in dynamic changes of magnetic field. The model of leg is reflecting the conductivity of muscle $\gamma_t = 0.67$ [S/m] only, e.g. [7, 8]. The duration of behaviour of induction power loss is too short (blue waveform on Fig. 4) with maximum pulse power about $P_{m\ \max} \sim 1.3 \times 10^{-6}$ [W]. We obtain the total energy losses of one magnetic pulse by integration

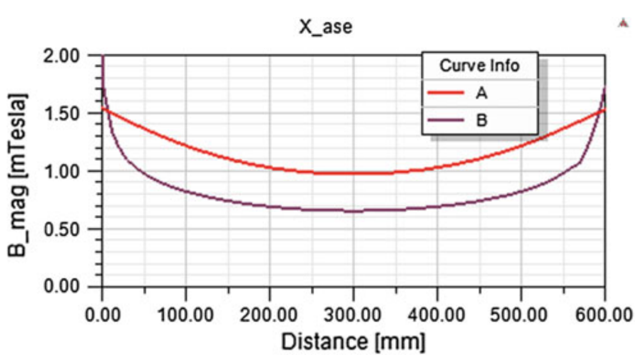

Fig. 2 Distribution of magnetic induction B inside cylindrical magnetic coil (input current 2A)

but these energy losses will be insignificant, approximately $W_m \sim 1.3 \times 10^{-9}$ [J].

In medical literature this biophysical effect is classified with the current density in tissue $\mathbf{J}_{t,}$ e.g. [9, 10]. Consequently the attention will be put on the distribution of current density in the model of leg. The Fig. 5 show our results.

Maximal top power in longitudinal axis is 1.25 µW and by rotation 30° is 1.75 µW. That is represented increasing of power possibly energy approximately 1.4 times.

2.3 Influence of Metal Implants and Their Orientation in Magnetic Field

Magneto therapy is a treatment method that is used quite often as an additional treatment for bone healing disorders after various traumatic conditions and orthopedic operations where metal implants can be implanted in the limbs. Metal implants are mostly made of materials that are non-magnetic, but these metals are usually highly conductive with conductivity substantially higher than any other types of tissue found in the human body. The following figure (Fig. 6) shows a part of the x-ray image of the lower limbs with metal implants. The patient was in this case advised to undergo magneto therapy.

The x-ray image shows the condition after a complicated fracture of the upper part of the lower leg that was treated by surgery—combined osteosynthesis by bolts and secured intramedullary nail. Basically, the intramedullary nail (hollow metal rod) longitudinally passes through the entire luminal cavity of the tibia bone. Based on this real case, a simplified numerical model has been compiled, which includes only a longitudinal rod without bolts. The orientation of the implanted rod is in the direction of the exciting

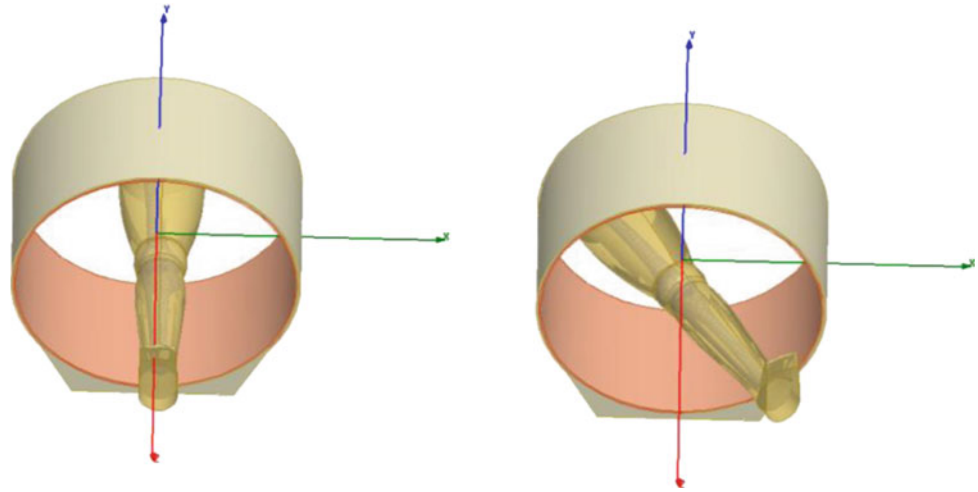

Fig. 3 Location of the leg in modelling and magnetic vectors specification, **a** The leg is oriented in direction z axis and is placed in center bottom quarter, **b** The leg is rotated 30º in direction z axis and is placed in center bottom quarter Model of leg in accordance with 166 cm stature and 66 kg weight of woman figure

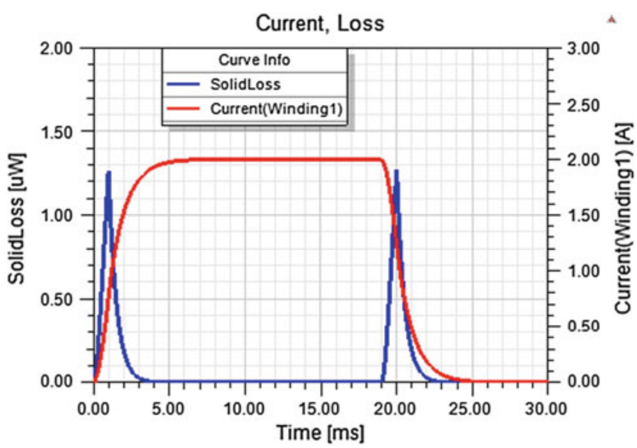

Fig. 4 Location of the leg in modelling and magnetic vectors specification

PEMFT. This means that the minimum induced current in the metal implant can be expected. In the simulation, both limb sizes are used, as shown in previous cases (Fig. 3a). At the same time, two diameters (8 and 15 mm) of implanted reinforcement were chosen for better understanding of the physical nature of the reinforcement. The leg model corresponds to a female figure of about 166 cm in height and 66 kg in weight.

Conducted numerical simulations confirm the expected theoretical assumptions that the metal implant will significantly influence the distribution of magnetic field in the tissue (Table 4). It is not possible to think about its influence separately. It will always depend on the total volume of tissue and the volume of metallic implants. In this case, the implant is in the direction of the magnetic field line, that is, the induced energy into its volume will be the lowest, but it will still significantly outweigh the energy induced into other tissues! The most induced energy is applied if the metal implant is oriented in its largest dimension perpendicular to the direction of the magnetic field force (in the x-axis direction). It can be expected that the metal screws connecting the fragments of the upper part of the tibia bone with its position at the center of the applicator and approximately perpendicular orientation to the field lines will also have a considerable effect on the amount of stored energy.

2.4 Influence of Volume Exposed Tissue and Their Composition

The theoretical preface, chapter 1.3 indicates that therapeutic impact will depend on the content of tissue which is inserted into the magnetic field. This situation stems from Eqs. (7, 8, 9).

The total energy loss is given by the degree of filling into the coil and is presented by cubic integral (9), e.g. [6].

The introduced example uses the same driving current pulse as is presented in (Fig. 4) but volume of tissue is plays major importance. The aim is to show how the induced current density will increase in the same shape model of leg but with leg 50% wider which presents 2.25× enlarged volume.

The duration of pulse induction power loss is too short again but with six times higher maximum power which is about $P_{m\ \max} \sim 8 \times 10^{-6}$ [W] and total energy losses of one magnetic pulse $W_m \sim 8 \times 10^{-9}$ [J]. The surface current density is about $\mathbf{J}_t \sim 0.022$ [A.m^{-2}] which is twice.

Main effect of magneto-therapy is the production of currents in the part of human body subjected to magnetic field. According to Reference of ICNIRP committee, e.g. [10], the value of induced current density range from 0.01 to 0.1 [A.m^{-2}] in human body and can influence nervous system. The range from 0.1 to 1 [A.m^{-2}] is able to cause health hazard and the changes in stimulation of nervous system were detect.

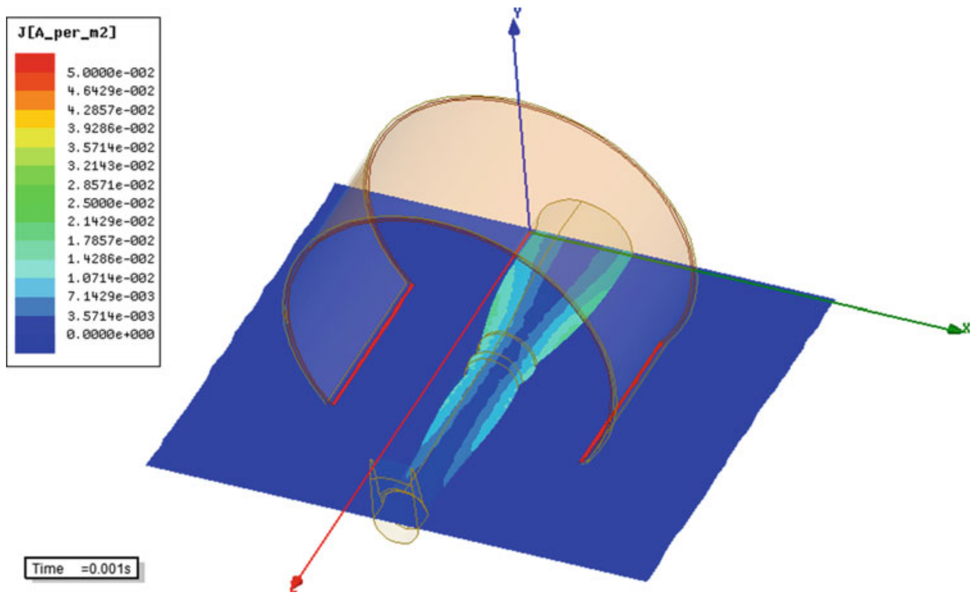

Fig. 5 Distribution of current density in the model of leg along longitudinal axis z

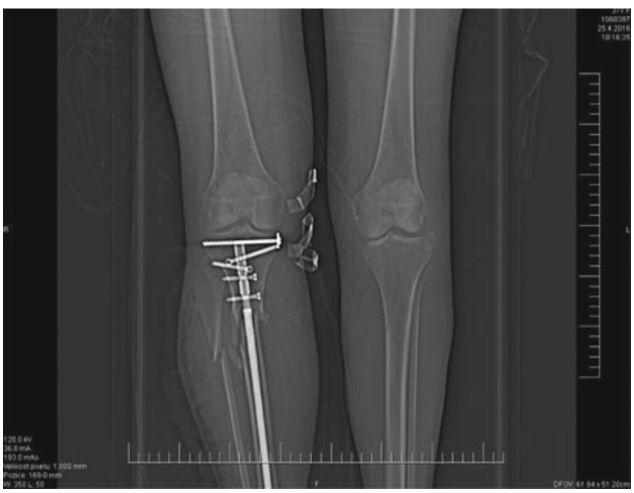

Fig. 6 X-ray image of the lower limbs with metal implants

Table 4 Influence of metal implants on maximum pulse power

$P_{m\ max}$ [μW]	Implant less	ϕ 8 mm implant	ϕ15 mm implant
	1.3	8.2	98.5
Model of lower limb with 2.25× enlarged volume			
	8	15.97	110.2

3 Conclusion

Approximate solution of magneto therapy describes the induced electric field in the body. It produces currents that are under the safety limits. The location and orientation body, volume exposed tissue and their composition has strong effect on distribution induced field and its energy impact. It means that the standard use of magneto-therapy is safe. The metal implants in body pose health hazard.

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