Med. & Biol. Eng. & Comput., 1980, 18, 758-764

Magneto- and electrophosphenes: a comparative study

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Abstract—*The purpose of this study was to compare the threshold values for magnetophosphenes and electrophosphenes under identical experimental conditions. Such comparisons between the phosphene types would increase our knowledge of the mechanism of the interaction between magnetic fields and electric current, respectively, and excitable tissue.*

The phosphenes were generated in the frequency range 10–45 Hz at moderate magnetic flux densities [up to 40 mT (400 G)] and electric currents up to 0·3 mA, respectively.

The first part of the study was devoted to the problem of how electrode location and consequent current directions influence the threshold values of electrophosphenes. In the second part a comparison was made of the threshold values for electrophosphenes and magnetophosphenes under identical experimental conditions apart from the stimulation method.

With electric-current stimulation in different directions no great differences were obtained with regard to the mean value for the threshold values within the frequency range 10–30 Hz. However, from 30 Hz upwards a significant difference developed between the threshold values for some of the curves.

When generating electrophosphenes and magnetophosphenes we found significant differences in the threshold values between approximately 25 and 45 Hz. Both types of phosphenes had a concurring sensitivity maximum at 20 Hz.

The deviations between the curves may be due, among other factors, to the generation of different current paths in electrical and magnetic stimulation, respectively.

Keywords—*Magnetophosphenes, Electrophosphenes, Extremely low frequency (e.l.f.) fields, Threshold values, Induced current densities*

1 Introduction

PHOSPHENES are defined as light sensations generated by stimuli other than the impact of photons, such as mechanical pressure upon the eye. Electric current and time-variable magnetic fields can also give rise to phosphenes, the so-called electrophosphenes and magnetophosphenes. The latter have been described by many authors (for electrophosphenes, see among others, BRINDLEY, 1955; CLAUSEN, 1955; SEIDEL, 1968; MOTOKAWA, 1970; KNIGHTON, 1973; and, for magnetophosphenes, among others D'ARSONVAL, 1896; MAGNUSSON and STEVENS, 1911-1912; SEIDEL *et al.*, 1968; LÖVSUND *et al.*, 1980). The greatest interest has so far, however, been directed toward studies of electrophosphenes. VALENTINUZZI (1962) and KNIGHTON (1973) have attempted to explain the origins of each phosphene type. Today it is regarded as certain that both magnetophosphenes (LÖVSUND *et al.*, 1980) and electrophosphenes (KNIGHTON, 1973) are generated in the retina.

First received 20th November 1979 and in revised form 7th February 1980

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BARLOW *et al.* (1947) made the first comparison between magnetophosphenes and electrophosphenes. They found, among other things, that both types of phosphenes are colourless and reach their greatest intensity at the periphery of the visual field. Among other characteristics, both types of phosphenes cause a certain degree of tiredness in the test subject and they are amplified in conjunction with eye movement. Phosphenes can be generated in the frequency range up to at least 90 Hz. The only difference between the two phosphene types that BARLOW *et al.* could detect was that closing of the eyelids increased the threshold value upon electrical, but not upon magnetic, stimulation. On the basis of these findings, the authors drew the conclusion that both types of stimulation activated the same neural structures.

Further comparisons between the phosphene types would increase our knowledge of the mechanism of the interaction between magnetic fields and electric current, respectively, and excitable tissue.

Thus, the purpose of this study was to compare the threshold values for magnetophosphenes and electrophosphenes under identical experimental conditions.

2 Material and methods

The method used to generate magnetophosphenes has been described in detail in an earlier paper (LÖVSUND *et al.*, 1980), and consequently only a brief description is given here.

A sinusoidal voltage for generating the magnetic field in the particular frequency range, 10–45 Hz, was obtained from a function generator. The signal was amplified in a power amplifier to which a U-shaped electromagnet with a variable air gap was connected. The electromagnet was placed over the volunteer's temples and adjusted to give the best possible fit. The flux density in the air gap was varied between 0 and 40 mT* (r.m.s.) during the experiments and measured with a gaussmeter (F. W. Bell 610Z, USA) in the vicinity of the retina (2 cm from the pole). A frequency counter (Racal 835, England) was used for accurate determination of the field's frequency.

Electrophosphenes were generated by means of an alternating current applied to the measuring object via skin electrodes (Medicotest A 15 S ECG electrodes, Medicotest A/S, Denmark) (Fig. 1). A sinus-shaped current in the frequency range 10–45 Hz was obtained from a function generator (Wavetek Model 114, California, USA). To eliminate any electrical hazards the current was conducted to the electrodes via an isolation amplifier. The frequency of the current was determined with a frequency counter (Racal 835, England).

The voltage across a resistor of 1000 Ω in series with the electrodes was measured with an electronic voltmeter (Electronic VAΩ meter, Philips PM 2404 Holland). The strength of the current through the electrodes was calculated and varied within the interval 0–0·3 mA (Fig. 1).

2.1 *Variation of electrode location*

The first part of this study was devoted to the problem of how electrode location and consequent current directions influence the threshold values of electrophosphenes.

The volunteers consisted of five healthy individuals (one woman, four men) in their twenties. Within this group (group I) the threshold values for electrophosphenes alone were determined for three different electrode locations: temple–temple, chin–bridge of nose and temple–bridge of nose. Luminance of the background lighting was 3 cd(candela)/m^2 and measured with a photometer (Hagner Universal Photometer, Model S2, Sweden) on the eye. (For a definition of luminance see e.g. WEAST, 1976). Light was provided by two photographic lamps. Each experiment began with adaptation of the volunteer to the background lighting for 10 minutes. The threshold values for the electrophosphenes were then determined for the three different electrode locations. The frequency of the current was increased from 10 Hz to 45 Hz in steps of 1 Hz and was then decreased in a corresponding way. For each frequency the strength of the current was increased until the volunteer stated that he/she could clearly see phosphenes. The strength of the current was then decreased until the phosphene effect completely disappeared. This threshold value was recorded. The mean value was calculated from two recordings at each frequency.

2.2 *Variation of the stimulation method*

In the second part of the study a comparison was made of the threshold values for electrophosphenes and magnetophosphenes under identical experimental conditions apart from the stimulation method.

In these tests 10 healthy and not colour defective subjects (five women, five men) in their twenties were studied. In this group (group II) the threshold values were recorded for both electrophosphenes and magnetophosphenes, partly with broad spectrum background lighting and partly with background lighting with a discrete wavelength of 572 nm, in both cases with a luminance of 3 cd/m^2. During stimulation with an electric current one electrode was applied to each temple. The electrodes were left in place also during the stimulation with a magnetic field but were not then connected to the current supply. Determination of the threshold values was carried out in the same way as for group I. Following a change in background lighting the volunteer was allowed to adapt for 10 minutes.

The experiments were performed with the volunteers in a supine position. Both the magnet poles and the electrodes were located in as similar ways as possible for the various individuals.

3 Results

In stimulation of the five volunteers in group I with electric current in different directions (various electrode locations) no great differences were obtained

* *1 T (tesla) = 10^4 G (gauss) = 1 Wb/m^2 (weber/m^2)*

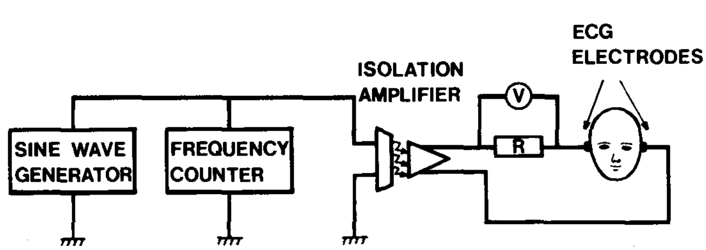

Fig. 1 *Experimental set-up for generation of electrophosphenes*

with regard to the mean value for the subjective threshold values within the frequency range 10–30 Hz (Fig. 2). A concurring sensitivity maximum (minimum stimulation) was found at 20 Hz. At frequencies higher than 20 Hz the curves agree relatively well without any local maxima or minima up to 30 Hz. However, from 30 Hz upwards, a significant difference develops between the threshold values for the temple–temple curve, on one hand, and the chin–bridge of nose and the temple–bridge of nose curves, on the other hand ($p < 0{\cdot}05$). The curves for chin–bridge of nose and temple–bridge of nose are not

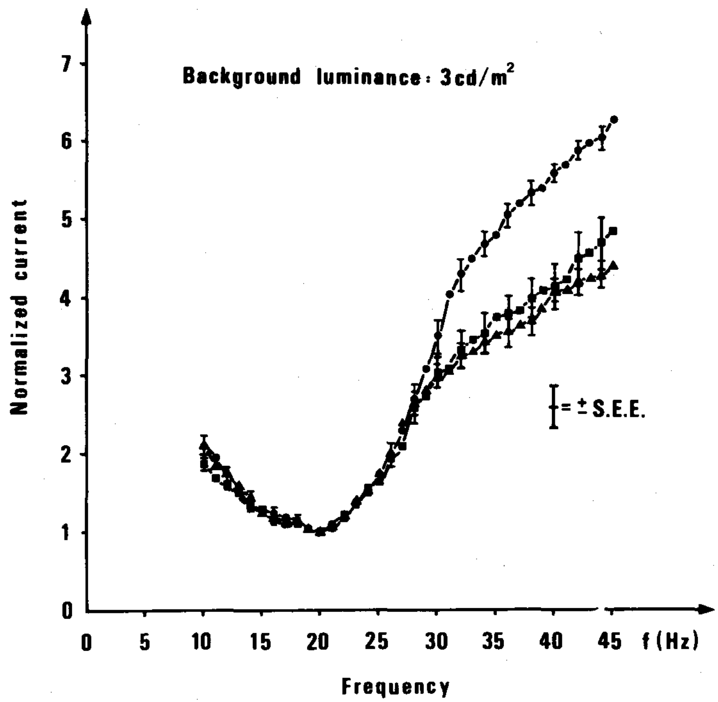

Fig. 2 *Threshold value curves for electrophosphenes with three different electrode locations and with a background luminance of 3 cd/m² (5 volunteers)*
● = *temple–temple,*
■ = *chin–bridge of nose,*
▲ = *temple–bridge of nose.*
(Normalised with regard to strength of current at 20 Hz)

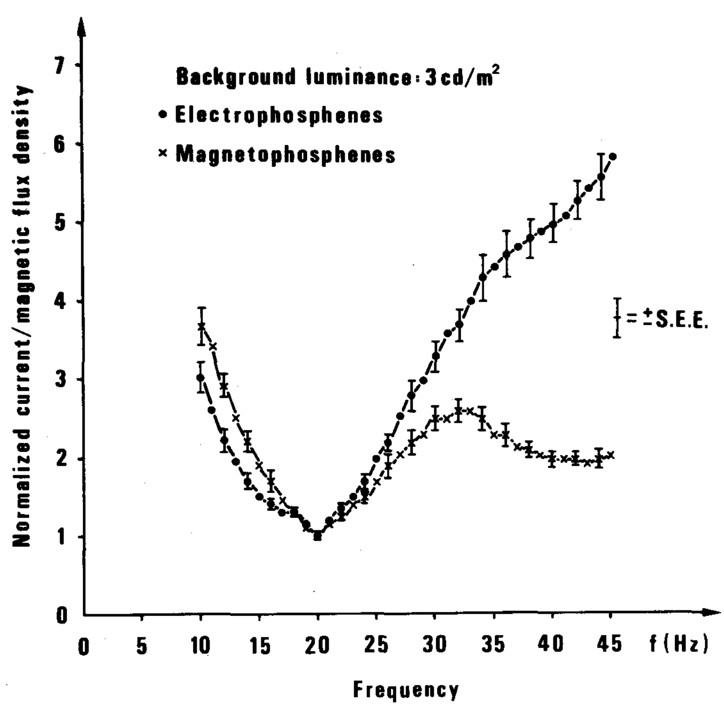

Fig. 3 *Threshold value curves for magnetophosphenes and electrophosphenes with broad spectrum lighting at a luminance of 3 cd/m² (10 volunteers)*

significantly different in that particular frequency range. For the statistical evaluations the Student's *t*-test for unpaired differences was used.

Fig. 3 shows the subjective threshold value curves for electrophosphenes and magnetophosphenes respectively in test group II with broad spectrum background lighting. Both curves have a concurring sensitivity maximum at 20 Hz. For frequencies from 10 to 20 Hz the electrophosphene curve shows a somewhat lower slope than the magnetophosphene curve, which implies significant differences ($p < 0{\cdot}05$) between the threshold value levels at frequencies between 10 and 17 Hz. For frequencies from 25 to 45 Hz there are significant differences ($p < 0{\cdot}05$) between the curves.

The magnetophosphene curve has a local sensitivity minimum at approximately 32 Hz, after which a new sensitivity maximum begins to build up at 40–45 Hz. The electrophosphene curve lacks a distinct sensitivity minimum in the frequency range 10–45 Hz even if a very slight change in the curve slope towards increased sensitivity in the upper frequency range can be seen.

In order to study how the threshold values for electrophosphenes are influenced by the spectral content of the background lighting the experiment was repeated but with a discrete wavelength of 572 nm, which is shown in Fig. 4. Here much the same results appear as in broad spectrum background lighting. The curves thus show a concurring sensitivity maximum at 20 Hz. The threshold values differ significantly ($p < 0{\cdot}05$) from 23 to 45 Hz. In the magnetophosphene curve a sensitivity minimum occurs at approximately 32 Hz, after which a new sensitivity maximum begins to build up at 40–45 Hz. In the electrophosphene curve only very slight evidence of this can be seen. In one respect, however, there is a variation between the results with broad spectrum lighting and monochromatic lighting. The difference in slope between the curves at frequencies below 20 Hz which occurred with broad spectrum background lighting (Fig. 3) does not appear with monochromatic lighting.

4 Discussion

In an earlier study (LÖVSUND *et al.*, 1980) similarities in the threshold values for magnetophosphenes and electrophosphenes were discussed on the basis of the available literature. Since the experimental parameters and test conditions varied both among the various studies of electrophosphenes themselves as well as between these studies and our investigations of magnetophosphenes, it was difficult to draw any detailed conclusions from these comparisons.

The study presented here, in which we have used almost identical experimental conditions when generating electrophosphenes and magnetophosphenes, shows significant differences in the threshold values between approximately 25 and 45 Hz. Both types of phosphenes have a concurring sensitivity maximum at 20 Hz. For frequencies below 20 Hz (with broad spectrum lighting) a significant difference between the curves appears in the range 10–17 Hz, which is,

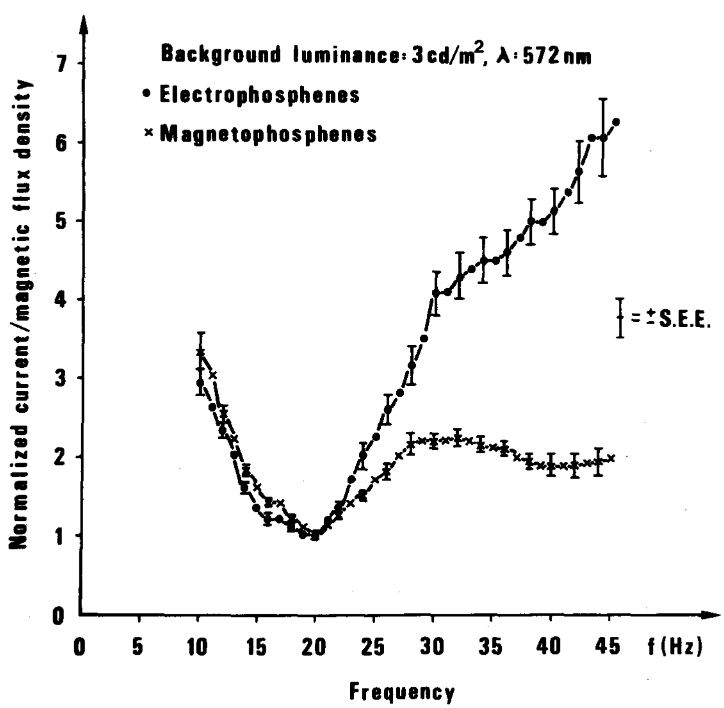

Fig. 4 *Threshold value curves for magnetophosphenes and electrophosphenes with monochromatic (572 nm) background lighting at a luminance of 3 cd/m² (10 volunteers)*

however, missing in monochromatic background illumination. The deviations between the curves can, as shown in this study, result from the different current directions occurring in electrical and magnetic stimulation, respectively, although differences in the principle of the mechanism of origin between the

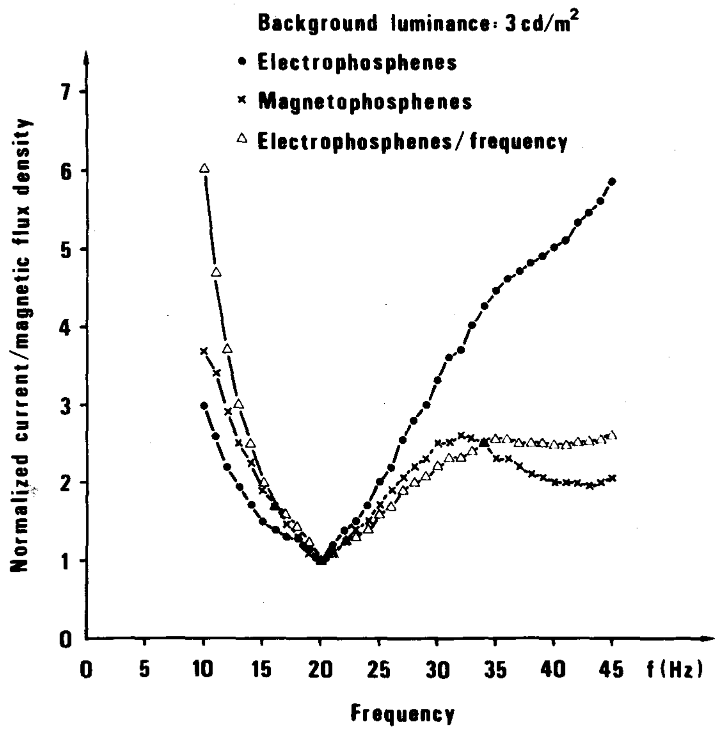

Fig. 5 *As Fig. 3, but with an additional curve where the threshold values for electrophosphenes have been divided by the frequency*

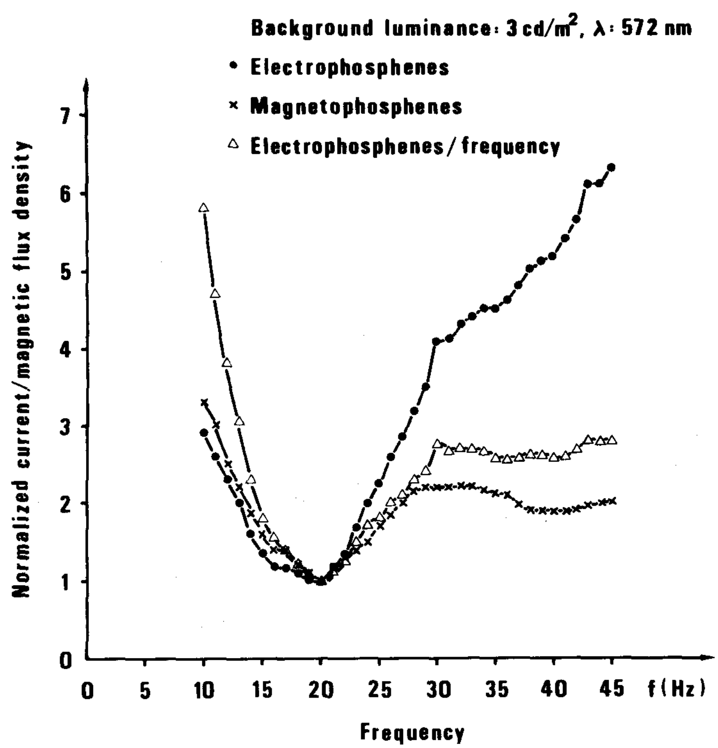

Fig. 6 *As Fig. 4, but with an additional curve where the threshold values for electrophosphenes have been divided by the frequency*

two phosphene types are also possible. The results from test group I do not give a threshold value curve for any of the three current directions, which agrees with that for magnetophosphenes in the complete frequency range. The differences between the various electrophosphene curves furthermore occurs only within the upper frequency range.

The volunteers in group I reported different positions of the phosphene sensation depending on the location of the electrodes. The volunteers in group II described partly different positions and partly a different nature of the phosphenes for the two ways in which these were generated. Influence of the electrode location on the position of the phosphenes has previously been reported by BRINDLEY (1955), among others. A change in character according to the type of stimulus might possibly be attributed to different neural elements being stimulated in the retina.

KNIGHTON (1973) proposed the hypothesis that electric current affects the synapses of the receptor cells. This hypothesis assumes a transretinal current path which, according to KNIGHTON, agrees well with physiological findings in conjunction with electrophosphenes. This transretinal current path is probably not obtained with stimulation by a magnetic field, but phosphenes are nevertheless generated, which may indicate that different neural elements are stimulated in the two cases.

The threshold curves we recorded for electrophosphenes in Figs. 2 and 3 may also be regarded as threshold value curves for the current density which is required in order to generate phosphenes as a function of the frequency. Since the law of induction states that the induced current density is directly proportional to the magnetic field and the frequency, it is possible to calculate the magnetic flux density required in order to induce the necessary current density. Division of the threshold values for the electrophosphenes by the frequency therefore gives a theoretical threshold value curve for magnetophosphenes (Figs. 5 and 6). Comparison of the theoretical and recorded magnetophosphene curves leads to fairly good agreement except with regard to the lowest and highest frequencies both in broad spectrum lighting and at 572 nm. The fact that the agreement is not total is, as reasoned before, probably associated with the somewhat different current paths which the two stimulation methods give or with the stimulation of different neural structures in the retina.

The experiments indicate that the nerve structures are sensitive to current density and, therefore, not directly to the magnetic field itself. A rough approximation of the current density which influences the retina (20 Hz) gives a value of 10^{-3} A/m^2, which should be compared to the current density of 10^{-2} A/m^2 regarded by KNIGHTON (1973) as necessary to excite the receptor synapses in the retina. Our estimated current density is also of the same order of magnitude as the threshold value for responses from the Aplysia neuron with endogenous activity (pacemaker) (WACHTEL, 1979); WACHTEL assumed that the nerve cell membrane itself constitutes the detector.

In this study our threshold curves show throughout a sensitivity maximum at 20 Hz, both for electrophosphenes and magnetophosphenes. This agrees with earlier findings for both types of phosphenes (see, for example, MOTOKAWA, 1970 and LÖVSUND *et al.*, 1980). A possible explanation of this maximum is discussed in LÖVSUND *et al.* (1980). We have not, however, been able to reproduce the five sensitivity maxima for electrophosphenes within the particular frequency range that MOTOKAWA and EBE (1953) found. This may be due to, among other things, the individual variations occurring, which are clearly shown by the somewhat different threshold values we obtained in this study and our previous investigation with other test subjects but with identical conditions. MOTOKAWA and EBE used in their study, for example, only one individual in several tests.

The study presented here shows for the first time a direct comparison of the threshold values for magnetophosphenes and electrophosphenes generated under identical test conditions. The deviations between the curves may be due, among other things, to the generation of different current paths in electrical and magnetic stimulation, respectively. Variation of current paths using different electrode locations creates differences between the threshold value curves in certain parts of the frequency range investigated.

Acknowledgments—We thank Miss Birgitta Svensson for skilful assistance. This work was financially supported by the Swedish Work Environment Fund (Grant No 74/138, 77/172).

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