Advantages of middle-frequency currents, amplitude-modulated by means of interference - for motor nerve and muscle stimulation -

- interferential current -

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The neurophysiological fundamentals of electrical stimulation of nerve fibres and muscles have been thoroughly investigated and are described in various scientific papers (6,7,8,9).
In any cases, however, the electrical parameters which determine the effectiveness of excitation have been merely considered in the therapeutic investigations. Consequently, no generally approved form of stimulation current has been established as yet. Especially, the advantages of middle-frequency currents for motor nerve and muscle stimulation that have been described by various authors for some decades already, have been neglected all the time.

Middle-frequency is defined by electrophysiological reasons in the range of 1 - 20 kHz (1,7,9). In this range, nerve fibres and muscle fibres cannot react to each sinusoidal half-wave of the stimulating current.
In middle-frequency stimulation, there are special principles of depolarization.
For muscle stimulation, a very different electromechanical coupling process as compared to low-frequency stimulation is proved (9,7).

A reasonable distinction between the applicable current forms and their biological efficacy is their classification according to frequency ranges.
There are four ranges:

1. Direct current (DC)		0 c.p.s.	Stimulation according to PFLUEGER'S law of excitation (5)
2. Low-frequency current (LF)	0 -	1000 c.p.s.	
3. Middle-frequency current (MF)	1000 -	100000 c.p.s.	Principle of "Apolar Stimulation" (3,9)
4. High-frequency current (HF)		100000 c.p.s.	Mainly thermic effects

A comparison of the different forms of current can only be made by means of certain physical and physiological parameters:

The stimulating process of biological tissue represents a process at the membrane, whereby changes of the ion distribution at both sides of the cell membrane occur. From the physical aspect, ions are to be understood as charges so that the basic process is the result of a transport of charges. Stimulation is achieved by supplying charges into the excitable structure, thus causing a change in the charge distribution at the cell membrane.

The parameter that determines the transport of charges is the electrical field intensity which is generated by the voltage applied between two electrodes.

The electrical field intensity $\bar{E}$ can be determined from the product of current density $\bar{s}$ and the specific resistivity ρ , respectively the reciprocal value of the conductivity κ of the surrounding medium ($\bar{S} = \kappa\bar{E} = \bar{E}/\rho$). The current density can be defined as current per area ($\bar{S} = I/A$). The product of current and voltage is the electrical power ($N = U \cdot I$).

In order to be able to compare and reproduce the the processes at the membrane, all the above mentioned values should be quantified as precisely as possible in each single case. The charge density which is defined as charge transport per area unit, represents a suitable measuring value for biologically effective currents. Its dimension is Coulomb per area unit (Coul/cm²). The charge density, however, may also be defined by the current density, multiplied by the time, so that the charge density as well as current density and time are relevant values in stimulation.

Consequently, the parameters that are important for electrical stimulation, are the following:

1. Charge density (µC/cm²)
2. Current density (A/cm²)
3. Time (s)
4. Frequency (1/s)

A further important parameter in comparison of different forms of current is the transition impedance $Z_{\ddot{u}}$). It represents a frequency-dependent resistance, consisting of an ohmic, a capacitive, and an inductive resistance. Except in the high-frequency range, the inductive resistance is negligible.

The transition impedance may be analysed as follows:

One component is the electrode impedance Z_{el}, resulting from the physical processes at the electrode boundaries, layers.

Another component is dependent on the medium between electrode surface and skin (R_{medium}), and results from the conductivity of electrode paste, respectively viscose sponge, and its geometric dimensions ($R = (\rho l)/A$). A further component of the transition impedance is the skin impedance which results from the layer structure of the skin.

Apart from the impedance acting vertically to the skin (Z_{tr}), between electrode and tissue, the so-called horizontal impedance (Z_{par}) shall be mentioned, which stands for the resistance parallel to the skin surface.

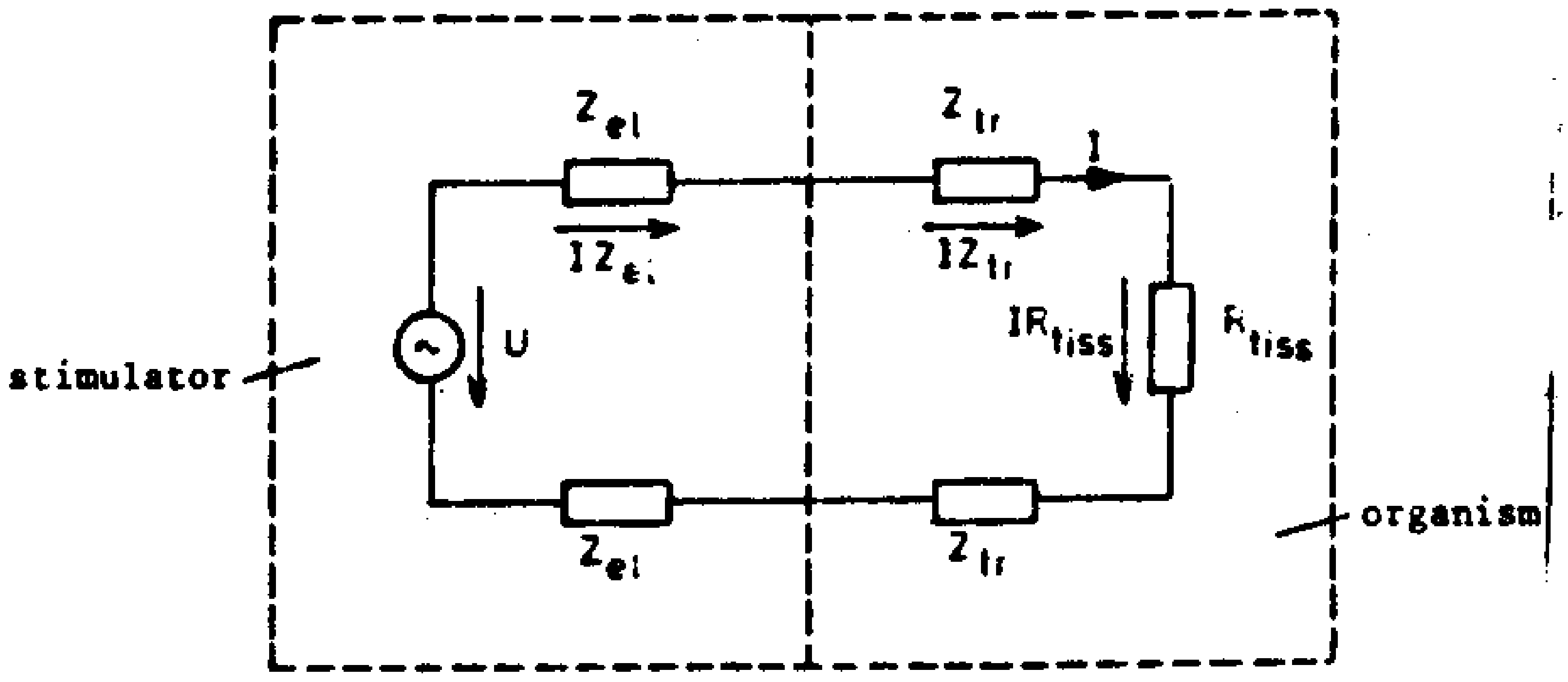

Fig. 1: Simplified electrical circuit diagram of a stimulator, the transition impedance, and the tissue to be stimulated under neglection of Z par.

In order to achieve the best stimulation effect, the transition impedance must be kept as low as possible compared to the resistance of the tissue. This keeps the loss of energy which is transformed, at the transition impedance, into heat, as low as possible, too.

The power acting at the biological membrane, which releases a stimulation process, is, for comparison of the different current forms defined as biological power. Its smallest value is defined here as biological threshold power.

Since all forms of electrical current can be split-up into periodic components by Fourier's analysis, we are taking in this paper only sinusoidal alternating currents to explain the dependance of the current effects on the frequency.

The following table gives the details for comparison

frequency		chemical	impedance electrode	impedance			Power total	Power useful		Power leakage		power threshhold		
range		erosion		skin tranversal			$N_{tot} = U I$ Heat production	biological						
	[Hz]		total	total	ohmic	$1/\omega C$		abs.	rel.	abs.	rel.	sens.	motor	pain
DC	0	+ +	+ + +	+ + +	+ + +	(∞) +++++++	U I	+	+	++	+++	++	+++	+++
NF	>0 -10^2		+ +	+ +	+ + +	+ + +	U I	+	++	+	++	+	++	+++
MF	>10^2 - 10^5		+	+	+ + +	+	U I	++	+++	+	+	++	+++	+++ ++
HF	>10^5		+	0	+ + +	0	U I	*1)	*1)	++++ *1)	++++ *1)	$(UI)_t$	$(UI)_t$	$(UI)_d$

1) Heat generation damages the tissue before the threshold of excitation is reached.

$(U \cdot I)_t$ = Power above the heat tolerance of the tissue

Table 1 shows the properties of different current forms in relation to the classification into the various frequency ranges:

Direct current with a frequency of 0 c.p.s., low-frequency of more than 0 up to 1000 c.p.s., middle-frequency of more than 1000 up to 100.000 c.p.s., and high frequency of more than 100.000 c.p.s.
Since the quantitative values of the impedance are greatly depending on the patient to be treated, we have not mentioned these quantitative values, and just given the description of the tendencies which is reflected in the number of small crosses.
In the first column it is shown, that with increasing frequency a reduction of chemical erosion is achieved.

The second column of the table shows the electrode impedance which is relatively high in the case of direct current and which diminishes with increasing frequency. This is due to the capacitive component of the electrode impedance which is parallel to the ohmic component. The higher the frequency, the more current components are flowing through this capacitive resistance without loss of heat.

The table does not show the inductive components of the impedance in the high frequency range.

The next column 3 reflects the state of the skin impedance, classified into total, ohmic, and capacitive resistance. Here, too, it can be shown that the value of the skin impedance decreases with increasing frequency, like in the case of the electrode impedance. This behaviour is as well depending on changes of the capacitive resistance as a function of frequency as mentioned above, while the ohmic component remains constant.
For direct currents the capacitive resistance is infinitely large, it decreases with increasing frequencies, and tends to zero in the high-frequency range.

Column 4 represents the total power supplied to the organism, which is finally completely transduced into heat. It is, for all forms of current, defined by the product of current and voltage (r.m.s.) and remains constant in all cases inspite of a change in frequency. Since the transition resistance decreases with higher frequency, the current flow is increasing with constant voltage, resulting in an increased power consumption of the tissue, and this in an increased production of heat. (In order to keep the power consumption constant, the voltage must be reduced with increasing frequency.)

Column 6 shows the leakage of power which changes with the frequency: it first decreases towards the middle-frequency range and increases, with higher frequency, towards infinity. The reason for this is that the leakage of power is a result of two opposed processes: One component, the transition resistance, is decreasing with higher frequencies; the other component, however, the threshold, increases again after passing a minimum, so that - in the high frequency range - the leakage power equals the total power. This depends on the fact that the total electrical energy supplied is transduced into heat before an excitation of any excitable tissue occurs.

Columns 7 shows the changes of the threshold power for thresholds of sensation, motor excitation, and pain perception. All these thresholds are passing a minimum in the low-frequency range; the distances between the single thresholds, however, are different: In case of direct current stimulation, the difference between sensation and motor threshold is only small, and the motor threshold is identical with the pain threshold.

This means that motor excitation is already causing discomfort in most of the cases.

The minimum in the low-frequency range means that only relatively low current intensities are required to achieve sensory or motor stimulation; since, however, the pain threshold is rather close to the two other thresholds, the therapeutic range that allows suprathreshold muscle stimulation is very restricted.

Middle-frequency currents, however, are considerably different:
Here, the sensory threshold is higher than in the low-frequency range; the motor threshold is somewhat higher, but the pain threshold is far from the two other thresholds, so that in most cases it is the intensity of motor stimulation that limits the current intensity, but not the excitation of nociceptors.

With an increase of frequency to the high frequency range, that is, over 100.000 c.p.s., the biological thresholds are so much higher that the heat produced by each current applied would lead to a thermic damage of the tissue before an excitation process would be triggered at all.

The biological useful power (column 5) is determined by physical and biological properties of the current, which show an opposed tendency depending on the frequency.
The useful power in the direct current range is relatively low, because the losses at the ohmic resistances in the transition and the tissue impedance are relatively high, and because of the fact that the threshold power is not at its minimum in that range.
In the low-frequency range, the effective power is higher because of the lower thresholds and the capacitive components of the impedance which already allow an easier penetration of the current.
With middle-frequency currents, the skin impedance is already very low so that only few current is lost at the skin surface. Also, the thresholds in the lower range of the middle-frequency have not increased that much as to require very high threshold power.

This means that the biological useful power is very high in the case of middle-freqeuency currents.

A further increase of the frequencies would cause a "running away" of the biological thresholds so that any stimulation would require high electrical power inspite of a continued decrease of the transition impedances. Reaching the high-frequency range, stimulation is no more possible due to the great thermic damage to the tissue.

As shown in the table, middle-frequency currents have the highest efficiency in stimulation of excitable biological tissue, due to physical and physiological reasons. Additionally, middle-frequency currents have further favourable and special stimulating physiological effects: the "Apolar Stimulation Effect" and the resulting possibility of "Transversal Stimulation". (3,4,9)
The fundamental of the apolar stimulating effect, the "Principle of Apolar Stimulation", means that stimulation processes are generated almost simultaneously under both electrodes when applying suprathreshold stimulation to a nerve in longitudinal direction.
The "Transversal Stimulation" which is only possible with middle-frequency currents, is the excitation of a nerve by means of transversally applied current flow, using two electrodes in opposite position to each other. This enables to stimulate any electrically excitable structures, independent of their position position in space inside the body.

Middle-frequency stimuli produce single or repetitive spikes only shortly after switching-on the current; with sustained current flow, these spikes are being followed by a reactive depolarization at the membrane (7). In order to influence excitable structures, repetitive stimulation is preferable in most of the cases. Unmodulated middle-frequency would not be suitable for this purpose. Therefore, the middle-frequency is modulated in amplitude in the low-frequeny range to enable the generation of low-frequent series of of action impulses in excitable structures. When applying such amplitude-modulated middle-frequency currents to the body by means of two electrodes, the maximum stimulating effect is achieved directly under these two electrodes, on account of the maximum current density existing at these sites.

Amplitude modulation may also be achieved by means of the so-called interference current principle, where two middle-frequency currents which are independant from each other and only slightly different in their frequencies, are applied to the body by means of four electrodes. Here, the amplitude modulation is generated in the area of superposition of the two currents, in the depth of the tissue. The site of maximum amplitude modulation and intensity can be predetermined by means of a defined electrode placement.

The resulting low-frequent modulation frequency equals the difference in frequency of the two superimposed middle-frequency currents. The maximum and minimum amplitude values resulting from the superposition, and thus the degree of modulation, are a function of the position within the tissue, the recording direction, and the time. They are changing in the rhythm of the beat frequency (interferential frequency).

The numerous particular physical and physiological properties of middle frequency currents amplitude-modulated by means of interference, make them favorable for motor nerve and muscle stimulation and that for prevention and retardation of disuse atrophy and for functional stimulation as well, evenly on account of their eminent advantages:

1. Lower skin impedance due to its capacitive components.
   In the skin, less energy is absorbed. The temperature increase is negligible. Higher energy can be applied transcutaneously without causing burns. Because of the favourable impedance relation (high impedance in the parallel direction to the skin surface, low impedance perpendicularly to it) we can transfer higher stimulation energy into deeper tissue layers and achieve a higher current density.
   This method allows to stimulate nerves and muscles more selectively.

2. With middle-frequency stimulation, a much higher force of contraction can be achieved, without nociceptor activation.

3. No electrochemical reactions under the electrodes.

4. Even with maximum intensity required for maximum motor stimulation, there is no danger of heart fibrillation (8).

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