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Frequency dependence of excitation–contraction of multicellular smooth muscle preparations: the relevance to bipolar electrosurgery

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ABSTRACT

Background: Bipolar electrosurgical tissue welding uses forceps-like electrodes for grasping the tissues and delivering high-frequency electric current (HFEC) to produce local heat, desiccation, and protein denaturation, resulting in the fusion of the contacting tissues. Although in this technique no electric current is flowing through the whole body to cause electric injury, depending on the frequency of applied energy, it may produce local excitation of intramural nerves, which can propagate beyond the surgical site potentially causing harmful effects.
Materials and methods: The effects of varying frequency of HFEC on tissue excitability in bipolar electrosurgical modality were studied *in vitro* using electric field stimulation (EFS) method on multicellular smooth muscle strips of rat vas deferens. Contractile response to 5-s-long sine wave EFS train was taken as the measure of excitation of intramural nerves.
Results: EFS-induced contraction consisted of phasic and tonic components. The amplitude of both components decreased with increasing frequency, with tonic component disappearing at about 10 kHz and phasic component at about 50 kHz. Because components of EFS-induced contraction depend on different neurotransmitters, this indicates that various neurotransmitter systems are characterized by distinct frequency dependence, but above 50 kHz they all become inactivated. Bipolar electrosurgical sealing of porcine gut showed no difference in the structure of seal area at HFEC of 67 and 533 kHz.
Conclusions: EFS frequency of 50 kHz represents the upper limit for excitation. HFEC above 50 kHz is safe to use for bipolar electrosurgical tissue welding without concerns of excitation propagating beyond the surgical site.

1. Introduction

Electrosurgery uses high-frequency electric current (HFEC) passed through the tissue to create the desired clinical effect *via* locally induced diathermy [1]. Among its common applications, such as cutting, coagulation, desiccation, and fulguration, electrosurgical tissue welding is increasingly viewed as a viable alternative to the traditional mechanical means of

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reconnecting the tissues, which are based on using the suture, metal staples, or clips [2]. In its bipolar mode, this technique uses HFEC to produce diathermy between tightly pressed tissues against each other [1–3]. The HFEC is usually delivered using bipolar forceps-like electrodes for grasping the tissues and applying pressure to them [4,5]. The two tines of the forceps perform the active and return electrode functions, and only the tissue grasped is included in the electric circuit, making separate patient "return" electrode characteristic of monopolar electrosurgery mode unnecessary. Localized HFEC passing through the grasped tissues induces thermal tissue damage, which depends on the size and shape of the bipolar electrodes, exerted pressure, and the parameters (power, frequency, waveform, and duration) of the high-frequency (HF) electric energy. If all parameters are optimal, the heat generation, desiccation, and protein denaturation results in fusion or "welding" of the contacting tissues confined to the area of the electrodes, which can withstand distraction force comparable to the force achieved for traditional sutured joints [6].

Power and duration of the applied electric energy have to be such that to prevent overheating and tissue burning to minimize necrotic damage and at the same time providing the strongest fusion possible. As these parameters change, so will the corresponding tissue effects [7]. Animal studies and clinical surgical experiences indicate that optimal frequency of the applied electric energy must range between 60 and 75 kHz [6]. However, despite bipolar welding technique does not require separate patient return electrode, which prevents net current flow through the patient's body thereby negating many of the safety precautions related to the clinical use of electric current, the International Electrotechnical Commission (IEC) and the Association for the Advancement of Medical Instrumentation only approve the use of the devices with the frequencies above 300 kHz [8].

Technically, the bipolar electrosurgical mode is similar to the electric field stimulation (EFS) method widely used in science to stimulate contractions of multicellular muscle preparation *in vitro via* excitation of intramural nerve fibers [9]. Thus, confined application of HF electric energy with the purpose of welding the tissues can also produce local excitation of intramural nerves, which can propagate to the central nervous system structure potentially causing undesirable effects. Because of the phenomenon of refractoriness, a short-term decrease in the excitability of nerve and muscle tissue occurs immediately after the manifestation of action potential [10]. The possibility of excitation decreases with increasing frequency of EFS. However, to our knowledge, systematic study of this phenomenon in the context of bipolar electrosurgical techniques, with the purpose of establishing the lowest frequency limit at which no potentially harmful excitation can occur, was not performed. Here, we have used rat vas deferens smooth muscle preparations with and without epithelial cell layers to establish frequency dependence of the contractions in response to the sine wave EFS *in vitro*. Our results show that at frequencies above 50 kHz no contraction can be induced, indicating that this frequency represents the lowest safe limit, which can be used for bipolar HFEC–mediated electrosurgical procedures.

2. Materials and methods

2.1. *Vas deferens preparation and recording of contraction*

Experiments were conducted on smooth muscle strips from the vas deferens of male Wistar rats weighing 200–250 g. Animals were killed by decapitation, their vas deferens was removed, and placed in the warm (37°C), oxygenated (95% O_2 and 5% CO_2) Krebs solution (in mM): 120.4 NaCl, 5.9 KCl, 1.2 $MgCl_2$, 1.2 NaH_2PO_4, 1.8 $CaCl_2$, 15.5 $NaHCO_3$, and 11.5 glucose (pH 7.4). Vas deferens was cleaned from connective tissue, its wall was cut along the axis, and longitudinal strips of 0.2–0.3 cm in diameter and 0.7–1.0 cm in length were excised from the parts adjacent to the prostate (prostatic portion). Smooth muscle strips with both epithelial layers removed and retained were used in the experiments.

Schematic diagram of the experimental arrangement is presented in Figure 1. For the recording of contractions, the strip was placed in the acrylic glass chamber continuously superfused with Krebs solution at 37°C with one end of the strip fixed still and another one attached to the capacitative force sensor with the baseline load of 3 mN applied to the strip. EFS was delivered *via* two Ag/AgCl wires positioned at one end of the strip from its top and bottom with direct contact with the tissue. The EFS consisted of sine wave trains of various frequencies (0.02–200 kHz), amplitudes (10–60 V), and durations (2-10 s) applied every 3 min, which was sufficient for complete restoration of basal tone. Contractile

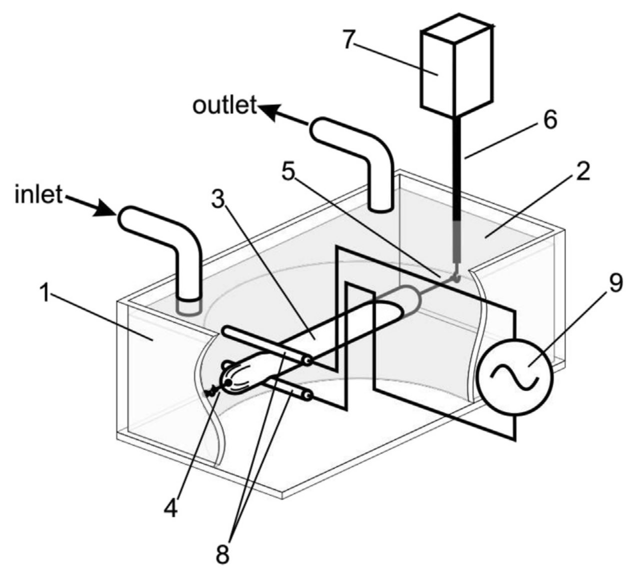

Fig. 1 – Schematic diagram of experimental arrangement. Acrylic glass experimental chamber (1) is continuously superfused *via* inlet and outlet tubes with Krebs solution (2). One end of the smooth muscle strip (3) is fixed still to the chamber wall *via* retainer (4) and another end *via* retainer (5) is attached to the lever (6) of the capacitative force sensor (7). EFS is delivered *via* Ag/AgCl electrodes (8) connected to the generator of HFEC (9). The drawing is not to scale.