Charge balancing strategies: electronics design impact on safety and electrode stability

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***Abstract*— Advances in electrodes hold the potential to improve the stimulation safety for implantable electrical stimulators, but electrode developers should understand some electronics design to optimise overall device safety.**

I. INTRODUCTION

Innovative research on electrode materials and manufacture promises ever more flexible electrode arrays, some with higher electrode density, or able to conform to the three dimensional shape of the target (CNS or PNS).

As electrode dimensions decrease, the surface density of charges on the electrodes increases, and with it, the risks of electrode corrosion and cell damage. Lilly's 1955 paper first suggested that balancing the charges delivered during stimulation was key to preventing damage [1]. In 1992, Shannon proposed an empirical safety criterion of charge-balanced waveforms, expressed as a relation between charge density and charge per phase [2]. Much work has sought to further our understanding of the mechanisms that mediate cell damage and electrode corrosion in chronic use, for various electrode dimensions and materials, and types of balanced waveforms; that may enable safe stimulation "to the right of Shannon's line" [3, 4].

Inspired by efforts to share knowledge across the many disciplines of our fields, such as the interpretation of electrochemical electrode characterisation, to improve stimulation safety [5, 6], we wish to discuss the impact, on overall safety, of compromises, made when designing the electronics of the stimulator, to comply with various sometimes conflicting, demands. In this presentation, we will consider the relationships between waveform, safety and stimulation efficacy from an electronics design point of view.

II. WAVEFORM, SAFETY AND STIMULATION EFFICACY

It is now generally accepted that the benefit of "balancing" a stimulation pulse is not to reverse all reactions like for like, but to maintain the electrode-electrolyte potential within a safe range, whilst maximising the charges that can be delivered safely during the cathodic phase. An imbalance between phases, charging, or discharging, the double layer capacitor, may allow the potential to "slide back" to a more favourable level [7, 8].

In the context of this paper, the stimulation efficacy is related to the ability of a cathodic pulse to elicit a desired response. Whilst electrodes are characterised in terms of charge capacity, the strength-duration curve reminds us that amplitude and duration must both be above a threshold for efficacious stimulation. For the electronics engineer designing the stimulator, the waveform should be described not only in terms of charge per phase, but also acceptable range of amplitude and duration. Owing to the potential for cathode-break and anodal excitation, as well as the inhibitory effect of depolarising pulses, this requirement applies not only to the cathodic phase, but also to the reversed pulse.

III. ELECTRONICS SAFETY, COMPLEXITY AND BLOCKING CAPACITOR

Circuits that produce current waveforms with controlled charges per phase are more complex (and larger) than those that deliver monophasic voltage pulses. Increasing design complexity, and the desire for smaller implants, increases likelihood of failure, because with increasing component density on a substrate, every connection is at higher risk of failure. Application Specific Integrated Circuits (ASICs) may be used to integrate more functions on a single component, the component density is more favourable, but routing and interconnections are not, and a single fault failure can lead to overload and rapid propagation of faults throughout.

Electronics engineers have long relied on an additional "blocking" capacitor in series with the electrodes, to block, or considerably limit, the passage of direct current through the electrodes. These enable simpler stimulators to achieve well balanced passive discharge, but increase the circuit's size. They may also provide safety under single fault conditions, but only for some output stage designs [9].

IV. CONCLUSION

Thanks to remarkable advances in the field, it is becoming possible to define electrode-specific safe stimulation parameters, unconditional on exact knowledge of the electrode-electrolyte interface (which is difficult to monitor chronically in vivo). As progress improves electrode and stimulation safety, an understanding of their impact on the electronics design will be needed to reach compromises between "ideal" electrical stimulation waveforms and implant circuit complexity, to optimise overall device safety.

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