TEACHING NERVE CONDUCTION TO UNDERGRADUATES: 
THE "TRAVELING FLAME" ANALOGY REVISITED

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A knowledge of the factors affecting conduction of bioelectric signals is important not only in disciplines related to the nervous system but also in cardiology for understanding the pathophysiology of arrhythmias and the mode of action of antiarrhythmic drugs. Although the cable properties of nerve are crucial to the understanding of the mechanism of nerve conduction, some popular textbooks (2, 3) make no mention of it at all. Authors who avoid discussing cable properties probably believe that most medical students will not appreciate the implications of the electric equivalent circuit diagram (Fig. 1). Such a surmise underlines the necessity of developing alternative strategies for explaining the cable properties, like the "traveling flame" analogy mentioned here. The analogy is not new; the name is. Also new is the proposal for extrapolating the analogy for deducing the factors affecting nerve conduction.

THE TRAVELING FLAME ANALOGY

A popular textbook of physiology (1) summarizes the analogy as follows: "A cigarette is a cylindrical structure filled with material at chemical potential which may be released as heat. It is excited by applying heat to it. This at first charges the cigarette with heat in a quite passive fashion, but when a critical temperature is reached, something new happens. The chemical energy of the cylinder is liberated as heat which spreads out from the active region and raises the temperature of the neighboring region. When the temperature here reaches a critical value, this region will also become active and so propagation will proceed. If this paragraph is now reread substituting the words nerve for cigarette, electricity for heat, a fair description of the nerve conduction will be obtained." 

In our introductory classes on nerve-muscle physiology, we present to our students the core concepts outlined above after elaborating them as follows. When one end of a rod is held over the flame, there are two ways in which the heat can get transferred to the other end. If the rod is a good conductor of heat, then in a very short time, the other end of the rod gets heated up due to transfer of heat through conduction. If, on the other hand, the rod is a poor conductor of heat but nevertheless combustible, e.g., wood, then it...
burns itself out, conveying the flame to the other end in the process. There are several differences between the two modes of heat transfer. 1) In the combustible rod, the transfer of heat is effected by the traveling flame, whereas in the conducting rod, only the heat travels; the flame remains at its own place. 2) A conductor can be used several times over to transfer heat; a combustible rod has to be replaced after every episode of heat transfer. 3) The heat transfer is much faster in conductors. 4) The heat transfer by combustion can be viewed as a high-fidelity transmission (the temperature of the flame remains constant as it travels), whereas the conduction of heat is invariably associated with decremental temperatures. 5) The high-fidelity transmission of the combustible rod is achieved at the expense of considerable energy expenditure. Transfer of heat by conduction is thus a far more efficient mode of heat transfer, the heat losses notwithstanding.

It would be incorrect to consider the two modes of heat transfer as mutually exclusive. In fact, the traveling of the flame is critically dependent on heat conduction. The flame must conduct heat to its adjacent area and raise its temperature to the ignition point. Hence, factors affecting heat conduction also affect the traveling flame. It would be of distinct advantage to harness the speed of conduction with the fidelity of the traveling flame. This can be achieved through a model system (Fig. 2) in which small combustible blocks are interposed between long conducting segments. These blocks, although boosting the transmission fidelity, also act as brakes on the speed of transmission. Therefore, longer lengths of conductor with fewer blocks would favor a higher transmission speed. However, the advantage is self-limiting. If the heat losses along the metal take the temperature below the ignition temperature of the combustible material, then the transmission would...
extinguish itself at the first block. Thus, for a given temperature of the flame, there will be an optimal length of the conductor at which it must be interrupted with a combustible thermal booster.

**NERVE CONDUCTION VELOCITY: ANALOGICAL CORRELATES**

The speed of heat transfer in the new model system would be contingent upon the variables relating to combustion and to conduction. The ignition temperature and the temperature of the flame are in the former category. The flame will travel fast if the ignition temperature of the combustible material is low (which would minimize the delay in ignition) and flame temperature is high (which enables a speedier heating of the area adjacent to the flame, since the rate of heat transfer is proportional to the temperature difference). The role of ignition temperature explains why the flame travels faster on an inflammable material. The role of flame temperature explains why a blazing flame travels faster than a smoldering fire.

Factors that would affect the speed of conduction are the specific heat of the conductor and its insulation. A low specific heat would allow quick rise of the temperature of the matter adjacent to the heat source. Better insulation prevents heat losses and thereby channels the heat along the conductor, resulting in speedier heat transfer. The corresponding analogues in nerve conduction are easily identifiable. Conduction in an unmyelinated nerve can be likened to the heat transfer through combustion, where the flame represents the action potential. Indeed, the action potential, as it is conducted on a membrane, has been called the “traveling cathode.” Saltatory conduction is analogous to the model system in Fig. 2.

Nerve conduction is speeded up if 1) the threshold for the action potential (comparable to ignition temperature) is low; 2) the peak positivity of the action potential (comparable to flame temperature) is high; 3) the axon has a larger diameter and, therefore, a higher axoplasmic conductance (comparable to the case where the combustible material is a good conductor of heat as well, e.g., a magnesium ribbon); 4) large lengths of the axon are myelinated so that they conduct electrotonically with action potentials occurring only at the nodes of Ranvier. Myelination minimizes the short circuiting of potentials across the membrane (comparable to heat losses in the absence of insulation) and reduces the membrane capacitance (comparable to a lower specific heat).

**USING THE ANALOGY**

We begin our lectures on nerve-muscle physiology with an overview of nerve conduction as indicated above, emphasizing the need of a potential/chemical energy stored in the conducting medium for transmitting signals without damping. It is in that context that the lectures on membrane potential are begun. Later, when we discuss the cable properties using the electrical equivalent circuit, the students enthusiastically associate the description with its analogy discussed earlier. They also retain the concepts better, as adjudged through periodic class tests.

**A CAVEAT**

A student once pointed out a paradox that a thicker axon conducts faster but a thicker stick burns slowly. The reason was explained to him as follows: the rate of the rise of temperature in a thin stick is faster because there is less material to be heated up (comparable to a lesser charge on the membrane). Nevertheless, the paradox does highlight the futility of stretching the analogy beyond a point.

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