

A COMPUTER MODEL OF CEREBELLAR PURKINJE CELLS

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Abstract—A mathematical computer model of frog Purkinje cells is generated on the basis of present-day morphological and physiological data. The model utilizes passive cable equations and the Hodgkin & Huxley equations describing ionic conductances in excitable membranes. It comprises 62 compartments, the active and passive properties being specified independently for each compartment. The morphological properties of the model were obtained from computer reconstruction and direct observation of Golgi-stained Purkinje cells. Three forms of activation were utilized to test the adequacy of the model: (1) antidromic invasion, (2) orthodromic invasion via the parallel fiber-Purkinje cell synapse, and (3) climbing fiber activation. It was shown that the electrophysiological parameters available in the literature make it possible to construct a model capable of demonstrating most of the electrical properties of Purkinje cells, such as antidromic invasion and the ability to generate simple spikes and spike bursts. Questions such as the mechanism of generation of climbing fiber bursts were analyzed. The model may be used as a heuristic tool to help in the analysis and interpretation of electrophysiology and as a prototype element in the construction of more complex computer simulations of neuronal circuits.

RIGOROUS mathematical models of the electrical activity of central neurons, besides being a powerful tool to test and interpret experimental data, can also be an essential component in the development of computer simulation of neuronal networks. Our interest in the Purkinje cell stems from its well understood morphology and function. In fact, this cell is unique in that its input, the climbing and the mossy-parallel fiber systems, have been totally described anatomically and functionally. Further, these inputs are extremely different from each other and represent the limits of afferent innervation. On the one hand, the climbing fiber input establishes a one-to-one pattern of innervation with the Purkinje cell and is probably the most specific afferent in the central nervous system. In contrast, at the other extreme of the continuum, the mossy fiber-parallel fiber complex represents the largest and most dispersed input to any central cell (RAMÓN Y CAJAL, 1911; cf. PALAY & CHAN-PALAY, 1974). From an electrophysiological point of view, the Purkinje cell is probably one of the most exhaustively studied neurons (cf. ECCLES, ITO & SZENTÁGOTAI, 1967; LLINÁS, 1969).

On a more general level the integrative properties of the Purkinje cell have gained further interest since the demonstration of dendritic electroresponsiveness (cf. LLINÁS & NICHOLSON, 1969, 1971; LLINÁS & HESS, 1976). This latter variable emphasizes the need for a modeling technique capable of handling a partially or totally active dendritic tree. The developing of such a model for the Purkinje cell offers the particular advantage that it must reproduce the responses to three distinctly different forms of activation, (1) the

antidromic invasion, (2) orthodromic parallel fiber mediated single spikes, and (3) the climbing fiber-activated spike burst. Meeting these stringent requirements provides an assurance of adequacy and a clarification of the mechanisms generating the complex bursting discharges which thus far have been purely speculative (ECCLES, LLINÁS & SASAKI, 1966; MARTINEZ, CRILL & KENNEDY, 1971).

Given the morphological richness of the Purkinje cell dendritic arborization, the very useful equivalent cylinder assumption developed for the spinal motoneuron (Rall, 1962a,b) will not be used here. While this decision introduces significant computational difficulties, it does, however, extend the model to trees not following the 3/2 constraint implicit in this concept. In fact, a preliminary quantitative analysis on frog Purkinje cells shows that the actual branching power averages 1.75 (J. McLAREN, personal communication).

In an important new development in neuronal modeling for the spinal motoneuron, DODGE & COOLEY (1973) combined the idealized equivalent cylinder cable model of Rall with the mathematical formulation of HODGKIN & HUXLEY (1952) for membrane ionic permeabilities. The model is composed of non-uniform cable segments representing the cellular morphology. In the present paper Dodge & Cooley's model is further developed and applied to Purkinje cells. The neuron is divided into a multitude of spatial components lumped together by the cable equations; the electrical phenomena in each compartment are governed by either the Hodgkin-Huxley equations (in the compartments representing excitable sections of the neuron membrane) or by passive R.C. properties. In this paper only passive dendritic arborizations will be considered; a future publication will consider