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Cardiac cell: a biological laser?

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Abstract

We present a new concept of cardiac cells based on an analogy with lasers, practical implementations of quantum resonators. In this concept, each cardiac cell comprises a network of independent nodes, characterised by a set of discrete energy levels and certain transition probabilities between them. Interaction between the nodes is given by threshold-limited energy transfer, leading to quantum-like behaviour of the whole network. We propose that in cardiomyocytes, during each excitation–contraction coupling cycle, stochastic calcium release and the unitary properties of ionic channels constitute an analogue to laser active medium prone to "population inversion" and "spontaneous emission" phenomena. This medium, when powered by an incoming threshold-reaching voltage discharge in the form of an action potential, responds to the calcium influx through L-type calcium channels by stimulated emission of Ca^{2+} ions in a coherent, synchronised and amplified release process known as calcium-induced calcium release. In parallel, phosphorylation-stimulated molecular amplification in protein cascades adds tuneable features to the cells. In this framework, the heart can be viewed as a coherent network of synchronously firing cardiomyocytes behaving as pulsed laser-like amplifiers, coupled to pulse-generating pacemaker master-oscillators. The concept brings a new viewpoint on cardiac diseases as possible alterations of "cell lasing" properties.

Keywords: Laser; Cardiac cell; Calcium-induced calcium release; Quantum resonator

1. Introduction

Impressive developments in biomedical sciences in recent years have greatly enhanced our understanding of the molecular basis of cell functioning. However, despite the gathered evidence, we still lack clear insights into the precise mechanisms that are responsible for cell functionality. With the progress in genomics and proteomics, it is becoming increasingly clear that this information does not reside in the genome alone, and probably not even in individual proteins that genes code for, as no real biological functionality is expressed at these levels (Noble, 2006a,b). There is growing recognition that to comprehend the true functioning of biological entities, it is necessary to understand complex molecular interactions in their natural cellular environment and precise spatio-temporal topology (Bassingthwaighte and Vinnakota, 2004; Greenstein et al., 2004) by defining essential concepts of regulatory systems forming their physiological behaviour.

In parallel, significant advances in physics and engineering sciences are occurring, with nanosciences and photonics among the most pronounced examples. Despite the fact that these scientific domains are oriented towards phenomena that are far from biological ones, we are now uncovering more and more analogies between living biological structures and artificially engineered nanodevices. We believe that these resemblances are not just coincidences, but that they reflect deep structural and functional similarities between cells and quantum electronic components. In this contribution, we would like to focus on one such emerging analogy: the biological "laser-like" properties of cardiac cells.

The LASER (light amplification by stimulated emission of radiation) is a well-known device producing an intense monochromatic beam of coherent light, engineered on the principles of the quantum theory of light (Einstein, 1905). The quantum theory of radiation and its interaction with matter is based on the concept of discrete energy quanta (photons) that can be absorbed by atoms or molecules, inducing electronic tran-

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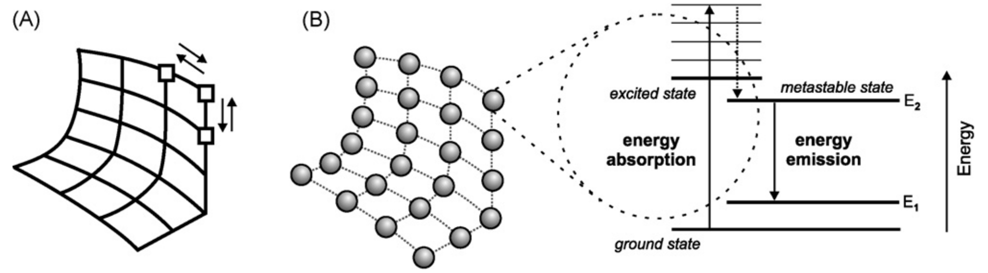

Fig. 1. (A) Simplified diagram of a cardiomyocyte model comprised of arbitrary mesh with coupled differential equations. (B) The proposed new model of cardiac cells, based on quantum resonator analogy. Cells consist of a network of independent sub-units, nodes, each having its discrete energy levels and energy transition probabilities ($E_{1,2}$—metastable energetic levels).

sitions to energetically higher, excited levels. From the excited electronic state, the electrons return to the ground state, and this transition is accompanied by the emission of another quantum whose energy is proportional to the energy level difference. The transition from excited to ground state can be either *spontaneous* or *stimulated* by the absorption of another photon. Based on these principles, the groups of Townes (Gordon et al., 1954, 1955) and Basov and Prokhorov (1954) simultaneously built the first prototype of a microwave maser in 1953, followed by the development of the first laser by Maiman (1960) as a variation of the same principle applied to visible light. The practical realisation of laser utilizes the existence of metastable energetic levels in certain materials, where the atoms can reside until population inversion is achieved. *Population inversion* denotes a situation when electrons-excited by an energy source (the "pump")—are dominantly located in the higher energy (excited) metastable state, from which a massive emission of light can take place while electrons are transited to the ground state (or a lower metastable) level. This effect allows incoming light to be amplified by the stimulated emission of radiation. In addition to the requirements for a defined atomic or molecular structure of the laser's active medium, carefully designed geometry (an *optical resonator*) needs to be applied to effectively combine the processes of spontaneous emission and light amplification by stimulated emission. The resulting light output has unique properties which include directionality, monochromaticity, high power and coherence.

2. Outlines of the concept of cardiomyocytes as quantum resonators

In the present chapter, we introduce the basic framework for a description of cardiac myocytes as biological "laser-like" quantum resonators. A more detailed discussion of the particular phenomena addressed in this concept is given in subsequent sections. We admit that the schemes introduced hereafter are quite general, addressing conceptual schemes and simplified feature comparisons in cardiac cells. Our intention is to apply an already-developed formalism of quantum electronics to the description of well-defined biological systems, such as cardiac myocytes, to put forward some interesting properties of cardiac cells that can be more easily viewed from the perspective of systems behaving like biological "laser-like" structures.

In comparison to commonly used cardiomyocyte models, based on coupled differential equations over arbitrary nodes in 3D space (Fig. 1A), we envision cardiac cells as an ensemble of independent functional units acting analogically to the network of atoms in laser active medium. In this view, the parameters describing each node involve a set of discrete energy levels and transition probabilities between these levels (Fig. 1B), whereas the interaction between neighbouring nodes is given by threshold-limited energy transfer leading to quantum-like behaviour of the whole network. Studies of biological phenomena, such as conduction pathways in microtubules (Hameroff et al., 2002; Penrose, 2001), DNA mutagenesis (McFadden and Al Khalili, 1999) and/or information processing in biological systems (Davies, 2005, 2004) and its synchronisation (Strogatz and Stewart, 1993), strongly emphasize quantum as well as wave features commonly found in the behaviour of biological systems. As we will show further, the analogy between lasers and cardiac cells includes such phenomena as the presence of "active medium", the capacity to produce "spontaneous emission" and "stimulated emission", "population inversion"-related issues and the oscillatory/resonant properties of cardiac cells. We believe that these features are not just a simple metaphor for the description of cardiac cells, but that they rather reflect a general principle driving the structure/function organization of supra-molecular complexes found at the mesoscopic level of cell description. In this contribution, we cite cardiac cells as an example to illustrate this likely widespread concept. Indeed, we believe that these features are not unique to cardiac cells, but can also be applied to other cell types. In this respect, cardiomyocytes being highly organized on the sub-cellular level are rather analogical to solid-state (crystal-based) lasers, whereas cells with less rigorous structures can be viewed as an analogy to lasers with turbid active media (gas, liquid).

In the presented framework, the heart can be viewed as a network of coherently oscillating laser-like structures, constituted from a set of pulse-generating pacemakers – the "master-oscillators", surrounded by amplifying blocks – cardiomyocytes. Among other consequences, this concept opens a new viewpoint on cardiac diseases as possible alterations of "cell lasing" properties, in contrast to simple changes of structure and/or function on the molecular level, strongly emphasizing more thorough investigation of non-linear integrative cellular physiology to unravel heart functioning.