Heliyon 8 (2022) e09084

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Controlling discharge mode in electrical activities of myocardial cell using mixed frequencies magnetic radiation

Clovis Ntahkie Takembo [a,b,*], Timoleon Crepin Kofane [c]

[a] Department of Electrical and Electronic Engineering, College of Technology, University of Buea I, P.O. Box 63, Buea, Cameroon
[b] Laboratory of Biophysics, Department of Physics, Faculty of Science, University of Yaounde I, P.O. Box 812, Yaounde, Cameroon
[c] Laboratory of Mechanics, Department of Physics, Faculty of Science, University of Yaounde I, P.O. Box 812, Yaounde, Cameroon

ARTICLE INFO

Keywords:
Myocardial cell model
Electromagnetic induction
Bursting
Mixed frequencies magnetic radiation
Bifurcation

ABSTRACT

Based on the standard Fitzhugh–Nagumo model for myocardial cell excitations and electrical activities, the effect of electromagnetic induction is considered and through which mixed frequencies magnetic radiation is imposed to detect the mode transition. Indeed, time-varying electromagnetic field can be induced when myocardial cell is exposed or surrounded by electromagnetic field and thus the effect of electromagnetic induction should be considered. From the analyzes of sampled series for membrane potentials, the improved model holds many bifurcation parameters and the mode of excitations and electric activities can be detected and observed in larger parameter zones. It is found that apart from exciting a myocardial cell, the mixed frequencies magnetic radiation can promote mode transition to bursting type behavior as the frequency is increased as well as suppress the electrical activities to quiescent state under high intensities magnetic radiations, which are consistent with biological experiments.

1. Introduction

The assessment of electrical and oscillatory activities of myocardial cell is highly relevant in understanding its functional and new characteristic states [1, 2, 3, 4, 5]. These characteristic states include quiescent, spiking, bursting and chaotic states, are closely linked with normal activities. Consequently, abnormal characteristic states could be linked with diseased states, resulting in abnormal heart rhythms, especially when the cardiac system is invaded or injured [6, 7, 8]. However, many cardiac arrythmia mechanisms leading in death remain unclear [9, 10]. In this light, many research studies have been devoted both experimentally and theoretically in understanding the mechanism of pace-making rhythms of the heart. Experimentally, spike, spike-burst and burst phase synchronization of various oscillatory patterns of intracellular calcium ion concentration were recorded in cultured cardiac myocytes [11]. Clusters of myocardial cells produce spontaneous oscillations and capable of responding to external stimulus, which modifies heart rhythms [12]. Due to the complex electrophysiological nature involves in heart beat, a detailed analyzes of these processes requires an elaborated and reliable mathematical model. The Hodgkin-Huxley equations [13] and it reduced form including the FitzHugh-Nagumo or Van der Pol equations [14, 15, 16, 17] can exhibit the natural expression of a myocardial electrical and oscillatory activities. Using these various models, many researchers have investigated mode selection and synchronous transition in cardiac tissue under some internal or external factors. Ji et al. [18], investigated bifurcation events in intracellular calcium ions oscillations using a modified mathematical model. Takembo et al. [19], reported localized modulated wave pattern in cardiac tissue by modulational instability under thermal effect. Lan et al. [20], reported noise-induced synchronous oscillations cardiac tissue. Hamadi et al. [21], studied stochastic synchronization in the beating of coupled cardiac cells. Zhang et al. [22], investigated the dynamics of spiral waves in cardiac tissue with inhomogeneity. Indeed, the electrocardiogram (ECG) usually used by cardiologists during initial medical consultation reveals oscillations with diverse spatial and temporal scales closely related to normal physiological or pathological states.

Contraction of myocardial cells is accompanied by complex electrophysiological activities with complex electrical activities. As such, electromagnetic induction is set up in cardiac tissue volume by the changes in distribution of ion concentration during the initiation and propagation of electric signal from the sinoatrial nodes. This effect of electromagnetic induction has been introduced into the research of myocardial

* Corresponding author at: Department of Electrical and Electronic Engineering, College of Technology, University of Buea I, P.O. Box 63, Buea, Cameroon.
E-mail address: takembo.ntahkie@ubuea.cm (C. Ntahkie Takembo).

https://doi.org/10.1016/j.heliyon.2022.e09084
Received 11 October 2021; Received in revised form 27 December 2021; Accepted 7 March 2022

cells [23, 24, 25, 26]. For example Ma et al. [23, 24, 25], studied pattern formation and mode selection in electrical activities of myocardial cell under electromagnetic induction exposed to electromagnetic radiation. The authors further predicted two death mechanisms in cardiac tissue induced by the effects of electromagnetic induction and radiation. Modulated wave amplitude damping in cardiac tissue under electromagnetic radiation was equally reported in ref. [26]. Indeed, external electromagnetic radiation can change the excitability of cardiac tissue and neuronal networks. Many schemes have been proposed to eliminate abnormal rhythms by controlling electrical activities [27, 28, 29, 30]. Amongst the various methods produced, direct current stimulation (DCS) with high amplitude has gained prominence [30]. Despite the successes recorded, such method has adverse effects such as skin lesions from burns, mania or hypomania in patients with depression and many others. The effect of external electromagnetic radiation on the electrical activities of cardiac and neuronal cells as a controlling parameter could produce amazing results which can even beat the effects of DCS. In this paper, we study mode selection in the electrical activities of myocardial cell under electromagnetic induction exposed to high-low frequency electromagnetic radiation. This has remain unexplored on the myocardial cell electrical activities. Indeed, the experimental evidences of electromagnetic radiation on biological systems have been reported. Lisi et al. [31] reported the effect of electromagnetic radiations at a frequency of 50 Hz on the development of newborn rat cerebellar granule neurons. Xu et al. [32] also investigated the oxidative damage to mitochondrial DNA in primary cultured neurons exposed to 1,800 MHz radio frequency radiation. High-low frequency electromagnetic radiation, usually regarded as a two kinds periodic forcings is widely applied in nonlinear systems including commutation technologies, such that the high frequency modulates the signal while low frequency encodes the data. The application of this mixed frequencies radiation has revealed the improved model for myocardial cell holds more bifurcation parameters and the mode of electric activities can be selected in larger parameter region. In the next paragraph, we discuss the improved model setting.

2. Model setting and discussion

The simple mathematical two variables FitzHugh-Nagumo model [33] and other basic biological models [34, 35] can produce the main dynamical properties of myocardial excitation and electrical activities without considering electromagnetic induction. As earlier indicated above, the effect of electromagnetic induction on myocardial excitation and electrical activities should be considered [36]. This results from the fluctuation in the distribution and the density of magnetic flux across the membrane potential of cell as it is exposed to electromagnetic fields according to the physical law of electromagnetic induction. Thus using the additional magnetic variable and memristor, a new myocardial cell model under electromagnetic induction exposed to mixed frequencies magnetic radiation is defined as follows

$$\begin{aligned} \dot{x} &= -kx(x-a)(x-1.0) - xy - k_0(\alpha + 3\beta\phi^2)x + I_0 \sin \omega t, \\ \dot{y} &= (\varepsilon + \frac{\mu_1 y}{x+\mu_2})[-y - kx(x-a-1)], \\ \dot{\phi} &= k_1 x - k_2 \phi + A\cos(2\pi f t) + B\cos(2\pi N f t), \end{aligned} \tag{1}$$

with

$$I = \frac{dQ}{dt} = \frac{dQ}{d\phi}\frac{d\phi}{dt} = \rho(\phi)\frac{d\phi}{dt} = \rho(\phi)V = k_0\rho(\phi)x = k_0(\alpha + 3\beta\phi^2)x. \tag{2}$$

The variables x, y and ϕ describe the membrane potential, slow variable for current and magnetic flux across the membrane, respectively. $I_0 \sin \omega t$ represents the transmembrane current mapped from periodic forcing for stimulation current, with amplitude I_0 and angular frequency ω. $-kx(x-a)(x-1.0) - xy$ are nonlinear terms translating the ionic transmembrane current on space unit of the membrane patch. $\rho(\phi) = \alpha + 3\beta\phi^2$ is a nonlinear function for the memductance of memristor, describing the modulation of time-varying electromagnetic field on membrane potential. α and β are constants dependent on the media. The term $-k_0\rho(\phi)x$ is a negative feedback term describing the induced current from the electromagnetic induction set up in cell. k_0 is the memristor coupling that bridges the membrane potential with the magnetic flux. k_1 describes the modulational effect of electromagnetic induction resulting from ionic transportation. k_2 is a feedback gain dependent on the media which calculates the level of polarization and magnetization created by the mixed stimulus magnetic radiation $A\cos(2\pi f t) + B\cos(2\pi N f t)$, having amplitudes A and B, frequencies f and Nf, with N being an integer that helps to discriminate low and high frequency. Indeed, the distribution and density of magnetic flux change when myocardial cell is exposed to continuous electromagnetic fields. In this work, magnetic radiation consisting of a linear combination of periodic forcings are imposed on the model for myocardial cell excitations and electric activities to detect mode transition. This could be very useful exploring the potential mechanism of myocardial electric signal processing exposed to multiple stimulations. It could equally be very useful in understanding some potential mechanisms of heart related disease. The proposed model here undoubtedly increases the number of control parameters, making it an efficient model for the eventual control of cardiac tissue electrical and excitations behaviors. To be consistent with previous work, we set various parameters as $a = 0.15, \mu_1 = 0.20, \mu_2 = 0.30, k = 10, k_1 = 0.30, k_2 = 1.0$ and $\varepsilon = 0.0002$.

3. Numerical simulation results and discussion

In the numerical studies, in order to calculate the time series for membrane potential we use the fourth order Runge-Kutta algorithm, time step is set as h = 0.001. The initial values are selected quiescent state x = 0.01, y = 0.01 and $\phi = 0.9$. Firstly in the absence of magnetic radiation, the amplitude of the external forcing current is set $I_0 = 0.6$, and then different angular frequency ω is imposed to detect the mode selection in electrical activities and results plotted in Figs. 1(a)-(d).

The results in Figs. 1(a)-(d) confirmed that under the effect of electromagnetic induction, electrical activities are changed through periodic like, spiking and even can develop into chaotic state by increasing the angular frequency ω. Furthermore, by fixing the frequency of the external periodic stimulus at $\omega = 0.08$, different amplitude I_0 are imposed to detect the mode selection in electrical activities and results plotted in Figs. 2(a)-(b).

It is found in Figs. 2(a)-(b) that different electrical modes in electrical activities could be observed with increasing the intensity of external periodic forcing. Indeed, periodic type oscillatory behaviors [in Fig. 2(a)] are modulated into spiking state [in Fig. 2(b)] by the increasing of external stimulus current. Results from Fig. 1 and Fig. 2 confirm that different oscillatory and periodic type behaviors are found in the sample time series of membrane potential and are controlled by external stimulus current. The controlled of electrical activities of excitable cells such as myocardial cells and neurons through the use of stimulus current forms the basis employing direct current stimulus (DCS) [37, 38] in influencing the nervous and cardiac systems.

To discern the effect of magnetic radiation on pattern formation and possible mode transition in electrical and oscillatory behaviors, the magnetic radiation is included on the magnetic flux variable as external stimuli and switched on at t = 1000 time units. As earlier stated we have considered radiation of the form $A\cos(2\pi f t) + B\cos(2\pi N f t)$, then different frequency disparity factor N are applied to detect mode transition and dynamical response in the calculated sampled time series for transmembrane potential, with results presented in Figs. 3(a)-(d).

The results in Figs. 3(a)-(d) confirmed that electrical activities of myocardial cell can produce mode transition when exposed to high-low frequency electromagnetic radiation as the frequency disparity factor N is increased. From the results presented, it is observed that for transient period less than 1000 time units, the time series in the sampled

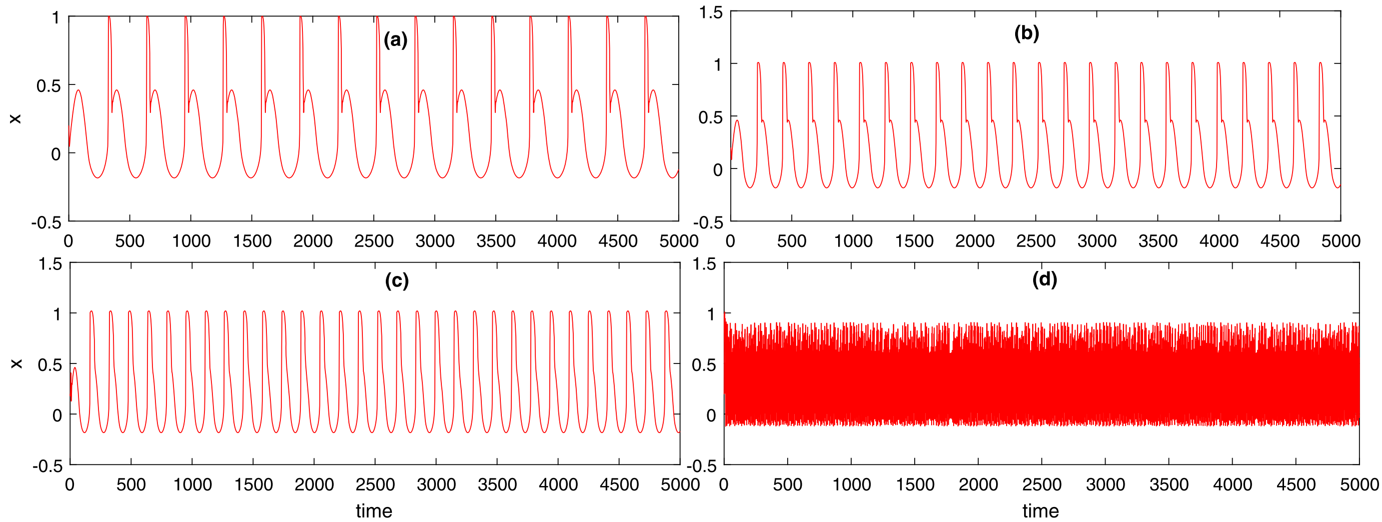

Fig. 1. Transition of electrical activities in an isolate myocardial cell in the absent of magnetic radiation and the amplitude of external forcing current set at $I_0 = 0.6$, (a) $\omega = 0.02$, (b) $\omega = 0.03$, (c) $\omega = 0.05$, (d) $\omega = 2.0$. The feedback gains of electromagnetic induction are set at $k_0 = 1.0$, $k_1 = 0.20$ and $k_2 = 1.0$.

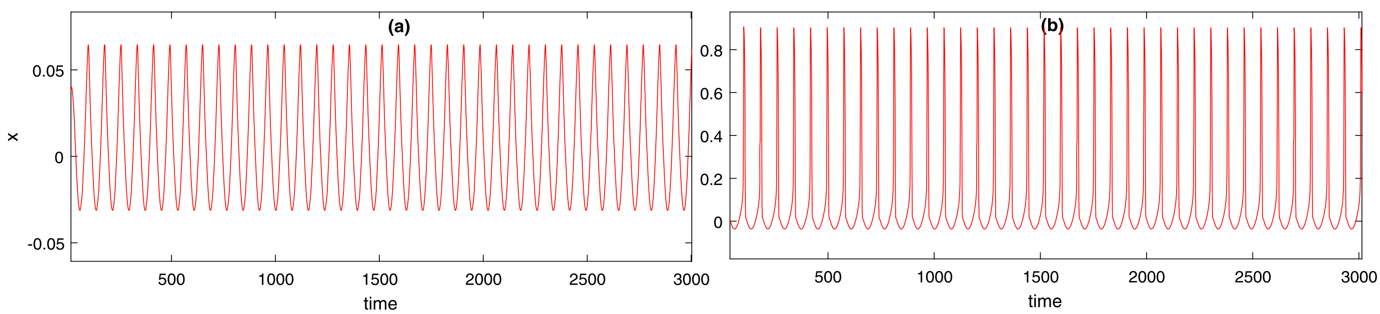

Fig. 2. Transition of electrical activities in an isolate myocardial cell in the absent of magnetic radiation and the frequency of external forcing current set at $\omega = 0.08$, (a) $I_0 = 0.05$, (b) $I_0 = 0.06$. The feedback gains of electromagnetic induction are set at $k_0 = 1.0$, $k_1 = 0.20$ and $k_2 = 1.0$.

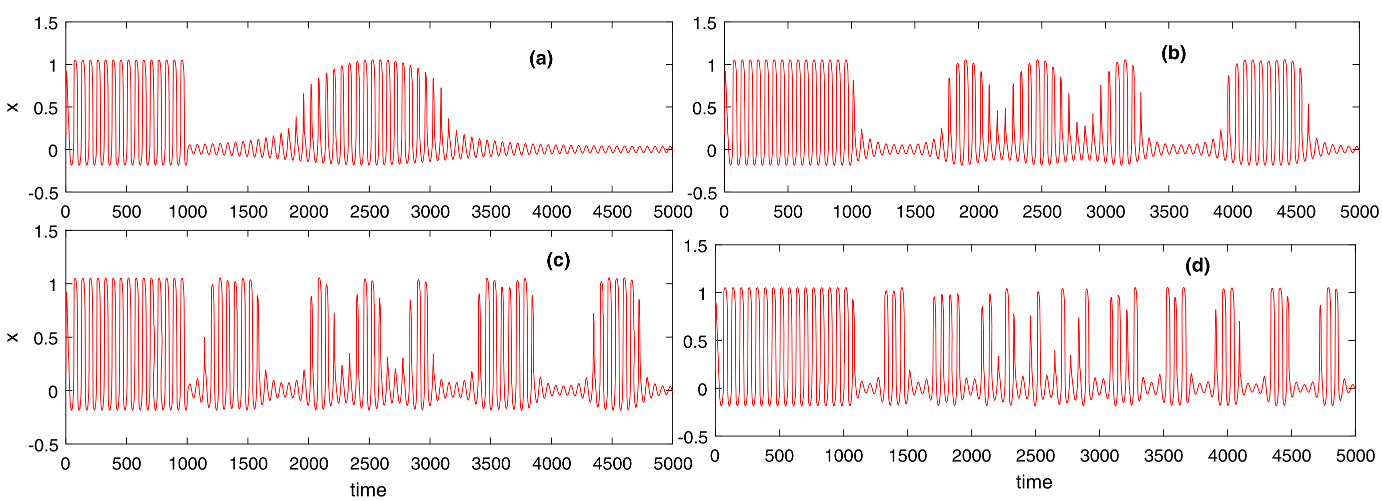

Fig. 3. Mode transition and dynamical response of electrical activities in an isolate myocardial cell approached by calculating the different membrane potentials as magnetic radiation is switched on at t = 1000 time units, when different frequency disparity factor N are applied. We set, $I_0 = 0.6$, $\omega = 0.1$, $k_0 = 1.0$, A = 2.5, B = 2.5, f = 0.0001 (a) N = 1 (b) N = 7 (c) N = 11 (d) N = 25.

membrane potential exhibit the dynamics. However, as magnetic radiation is included, different dynamical responses are observed, showing the effect of the radiation. Indeed, the electrical activities can produce one, four, six bursting behaviors with increasing N. To confirm the generality of the proposed model, we use another group of parameters; $I_0 = 0.6, \omega = 0.1, k_0 = -1.0, A = 1.7, B = 0.7, f = 0.0005$ and with different values of N selected, results are presented in Figs. 4(a)-(d).

It is confirmed that burst-like activities, with possible switch to chaotic behavior can be induced in the electrical activities under magnetic radiation. It confirmed that under negative feedback though k_0, in-

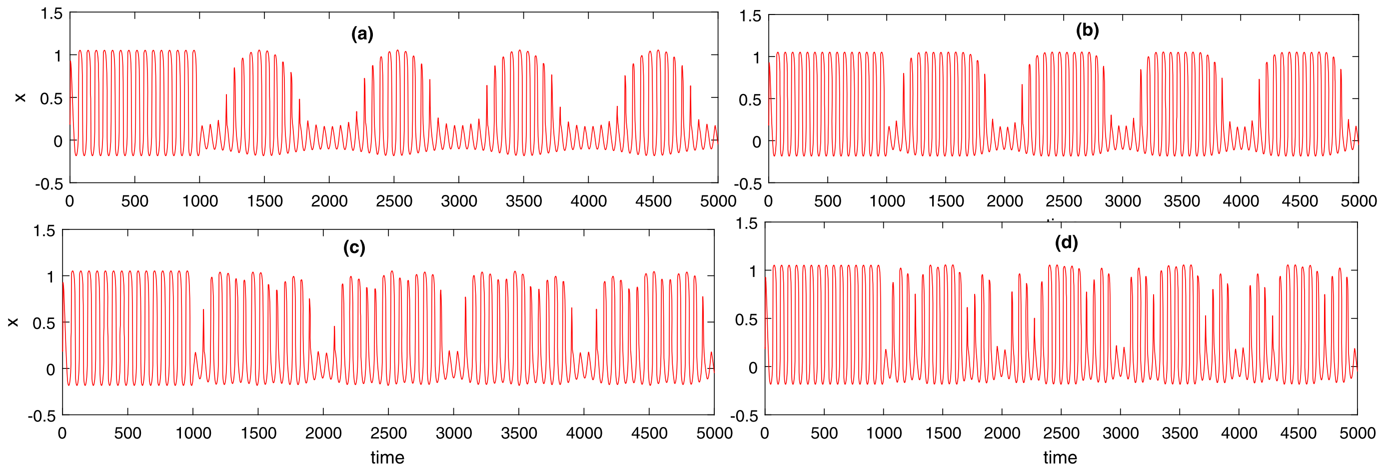

Fig. 4. Mode transition and dynamical response of electrical activities in an isolate myocardial cell approached by calculating the different membrane potentials as magnetic radiation is switched on at t = 1000 time units, when different frequency disparity factor N are applied $I_0 = 0.6$, $\omega = 0.1$, $k_0 = 1.0$, A = 1.7, B = 0.7, f = 0.0005 (a) N = 1 (b) N = 3 (c) N = 5 (d) N = 7.

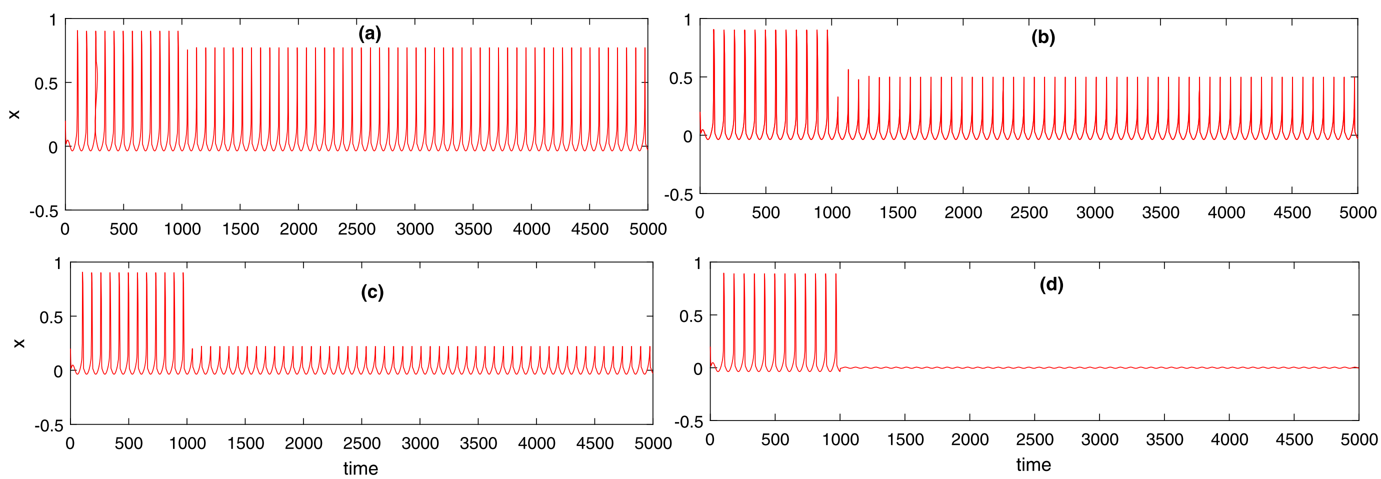

Fig. 5. Mode transition and dynamical response of electrical activities in an isolate myocardial cell approached by calculating the different membrane potentials as magnetic radiation is switched on at t = 1000 time units, when different intensities are selected with $I_0 = 0.06$, $\omega = 0.08$, $k_0 = 1.0$, f = 0.0, N = 1.0 (a) A = B = 0.05, (b) A = B = 0.055,(c) A = B = 0.06, (d) A = B = 2.0.

creasing N changes excitability with the possible emergence of chaotic patterns as observed. Furthermore, the frequency is fixed while the intensity of the radiation is increased and results are presented in Figs. 5(a)-(d)

The results in Figs. 5(a)-(d) indicate that bursting state in electrical activities can be suppressed under appropriate intensity of magnetic radiation. The potential mechanism is that when weak intensity electromagnetic field, the cell can select the suitable mode in electrical activities. However, as the intensity of the field is increased, polarization and magnetization take place on the cell thereby suppressing the electrical activities. Finally, the amplitude and intensity is fixed while the frequency is increased. Results are presented in Figs. 6(a)-(d).

From the results, the sampled time series for membrane potential of myocardial cell under to a continuous magnetic field show that the mode in electrical activities can be changed. The calculated time series for membrane potential in electric activities show that multiple modes (spiking and bursting) can be induced. Indeed, the transition between different oscillation behaviors of the myocardial cell could correspond to a possible transition to an abnormal or irregular heart rhythm, including atrial and ventricular fibrillation as well as ventricular tachycardia, closely associated with the loss of rhythm [39]. Apart from the intrinsic system parameters, the memristor coupling k_0 and the stimulus current with amplitude I_0 and angular frequency ω, myocardial cell excitation and electrical activities could be effectively control using the different amplitudes and frequency of external electromagnetic radiations A, B, N and f [40, 41].

In a summary, the proposed improved myocardial model holds more bifurcation parameters and the effect of high and low frequency magnetic radiation could be included. In the process, the effect of electromagnetic induction is considered in the improved FitzHugh-Nagumo model for myocardial cell via the third variable; the magnetic flux variable. The high and low frequency magnetic radiation is considered as a linear combination of two continuous electromagnetic fields. From extensive numerical simulations, multiple modes in electrical activities could be detected and observed in myocardial cell by synchronously adjusting many bifurcation parameters. Based on the model presented, Fast Fourier Transform analysis may also be performed to detect the coexistence of multiple modes in electrical activities of neurons and neuronal networks [42, 43]. Using the same scheme, synchronization in cardiac issue and neuronal work under electromagnetic induction [44, 45, 46, 47] could be investigated driven mixed frequencies stimulation. In that case, it could be useful to verify the shock of heart beat as a result of termination of heartbeat induced by turbulent-like behaviors exposed to high and low frequency magnetic radiation. Apart

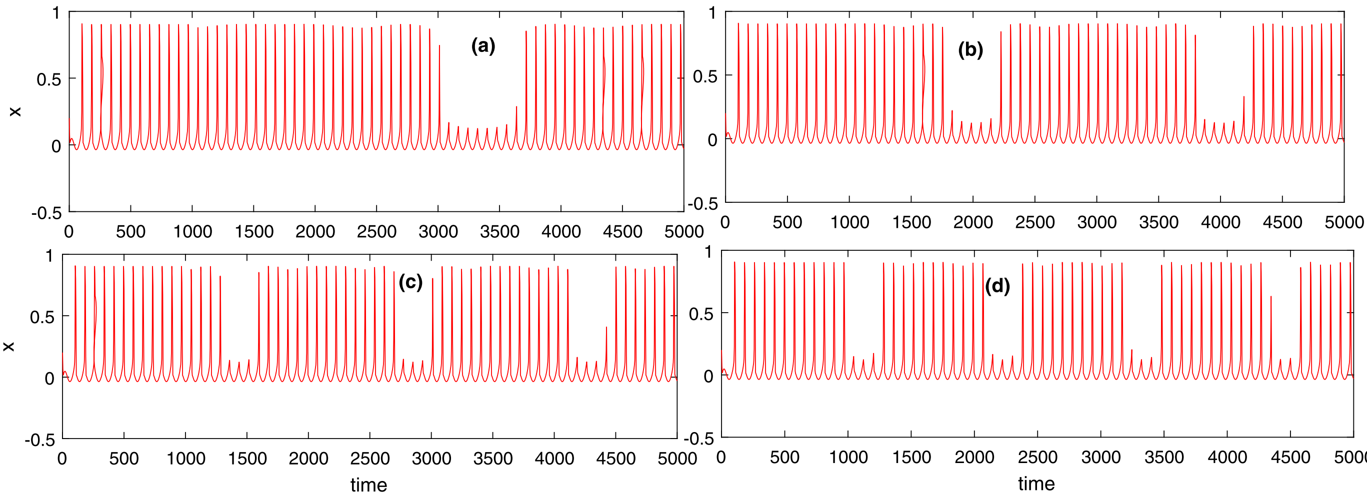

Fig. 6. Mode transition and dynamical response of electrical activities in an isolate myocardial cell approached by calculating the different membrane potentials as magnetic radiation is switched on at t = 1000 time units, when different frequency is selected with $I_0 = 0.06$, $\omega = 0.08$, $k_0 = 1.0$, A = 0.09, B = 0.09, N = 2.0 (a) f = 0.0003, (b) f = 0.0005,(c) f = 0.0007, (d) f = 0.0009.

from the high-low frequency electromagnetic radiation explored in our manuscript, future work could be dedicated towards possible stochastic generalization by using non-deterministic external radiation sources like colored noise. Secondly it would also be interesting to investigate the effect of high-low frequency electromagnetic radiation in neuron and neuronal networks via Hodgkin-Huxley model [13, 48].

4. Conclusion

A new model for myocardial cell excitation and electrical activities is proposed from the standard two-variables FitzHugh-Nagumo model by detecting the effect of mixed frequencies magnetic radiation. The dynamical behaviors detected and observed become more diverse and very much interesting by introducing many bifurcation parameters. The standard two-variables model and many of the previous studied model produces only mode in electrical activities driven by external stimulus. Thus, multiple modes in electrical activities of myocardial cell can be reproduced by changing more than four bifurcation parameters as the case maybe. In this work, the authors have argued that the distribution and density of magnetic flux fluctuate when myocardial cell is exposed to continuous electromagnetic fields. As such, we used the magnet flux variable together with the memristor in the model in accordance with the consistence of physical units. From the improved model, mixed frequencies magnetic radiation are included as external forcings on the magnetic flux variable and which is capable of generating a multiple of modes in electrical activities. This indicates that the excitations and electrical activities can be effectively controlled by magnetic radiation [49].

CRediT authorship contribution statement

Author contribution statement

Clovis Takembo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. Timoleon Crepin Kofane: Analyzed and interpreted the data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] J.R. Clay, R.L. DeHaan, Fluctuations in interbeat interval in rhythmic heart-cell clusters. Role of membrane voltage noise, Biophys. J. 28 (3) (1979) 377–389.
[2] T. Hayashi, T. Tokihiro, H. Kurihara, K. Yasuda, Community effect of cardiomyocytes in beating rhythms is determined by stable cells, Sci. Rep. 7 (2017) 15450.
[3] J. Satin, I. Kehat, O. Caspi, I. Huber, et al., Mechanism of spontaneous excitability in human embryonic stem cell derived cardiomyocytes, J. Physiol. 2 (2004) 559.
[4] C.B. Tabi, I. Maïna, A. Mohamadou, H.P.F. Ekobena, T.C. Kofane, Long-range intercellular Ca^{2+} wave patterns, Physica A 435 (2015) 1–14.
[5] L. Glass, Synchronization and rhythmic processes in physiology, Nature 410 (2001) 277–284.
[6] W.T. Clusin, Calcium and cardiac arrhythmias: DADs, EADs, and alternans, Crit. Rev. Clin. Lab. Sci. 40 (2003) 337.
[7] D.C. Michaels, E.P. Matyas, J. Jalife, Mechanisms of sinoatrial pacemaker synchronization: a new hypothesis, Circ. Res. 61 (1987) 704.
[8] D. DiFfrancesco, Pacemaker mechanisms in cardiac tissue, Annu. Rev. Physiol. 55 (1993) 455–472.
[9] H. Gonzalez, Y. Nagai, G. Bub, L. Glass, A. Shrier, Reentrant waves in a ring of embryonic chick ventricular cells imaged with a Ca^{2+} sensitive dye, Biosystems 71 (2003) 71–80.
[10] G. Bub, A. Shrier, L. Glass, Spiral wave generation in heterogeneous excitable media, Phys. Rev. Lett. 88 (2002) 058101.
[11] H. Gu, B. Pan, J. Xu, Experimental observation of spike, burst and chaos synchronization of calcium concentration oscillations, Europhys. Lett. 106 (2014) 50003.
[12] C.N. Takembo, A. Mvogo, H.P. Ekobena, T.C. Kofane, Modulated wave formation in myocardial cells under electromagnetic radiation, Int. J. Mod. Phys. B 32 (2018) 1850165.
[13] A.L. Hodgkin, A.F. Huxley, A quantitative description of membrane current and its application to conduction and excitation in nerve, J. Physiol. 117 (1952) 500–544.
[14] R. FitzHugh, Impulses and physiological states in theoretical models of nerve membrane, Biophys. J. 1 (6) (1961) 445–466.
[15] J. Nagumo, S. Arimoto, S. Yoshizawa, et al., An active pulse transmission line simulating nerve axon, Proc. IRE 50 (1962) 2061–2070.
[16] C.B. Tabi, Dynamical analysis of the FitzHugh-Nagumo oscillations through a modified Van der Pol equation with fractional-order derivative term, Int. J. Non-Linear Mech. 105 (2018) 173–178.

[17] M.E. Brandt, Visual and auditory evoked phase resetting of the alpha EEG, Int. J. Psychophysiol. 26 (1997) 285–298.
[18] Q.B. Ji, Y. Zhou, Z.Q. Yang, X.Y. Meng, Bifurcation scenarios of a modified mathematical model for intracellular Ca^{2+} oscillations, Chin. Phys. Lett. 35 (5) (2015) 050501.
[19] C.N. Takembo, H.P. Ekobena, Effect of temperature fluctuation on the localized pattern of action potential in cardiac tissue, Sci. Rep. 10 (1) (2020) 15087.
[20] L. Yuan, Z.Q. Liu, H.M. Zhang, et al., Noise-induced synchronous stochastic oscillations in small scale cultured heart-cell networks, Chin. Phys. B 20 (2) (2011) 020508.
[21] H. Hamada, H. Nomura, et al., Exploring the implicit interlayer regulatory mechanism between cells and tissue: stochastic mathematical analyses of the spontaneous ordering in beating synchronization, Biosystems 111 (2013) 208–215.
[22] J. Zhang, J. Tang, et al., The dynamics of spiral tip adjacent to inhomogeneity in cardiac tissue, Physica A 491 (2017) 304–346.
[23] F.Q. Wu, C.N. Wang, Y. Xu, et al., Model of electrical activity in cardiac tissue under electromagnetic induction, Sci. Rep. 6 (2016) 28.
[24] J. Ma, Y. Yang, C. Wang, et al., Mode selection in electrical activities of myocardial cell exposed to electromagnetic radiation, Chaos Solitons Fractals 99 (2007) 219–225.
[25] J. Ma, F. Wu, et al., Electromagnetic induction and radiation-induced abnormality of wave propagation in excitable media, Physica A 486 (2017) 508–516.
[26] C.N. Takembo, A. Mvogo, H.P. Ekobena, T.C. Kofane, Localized modulated wave solution of diffusive FitzHugh-Nagumo cardiac networks under magnetic flow effect, Nonlinear Dyn. 95 (2) (2019) 1079–1098.
[27] G. Wang, Y. Xu, M. Ge, L. Lu, Y. Jia, Mode transition and energy dependence of FitzHugh-Nagumo neural model driven by high-low frequency electromagnetic radiation, AEÜ, Int. J. Electron. Commun. 120 (2020) 153209.
[28] C.N. Takembo, M. Ekonde Sone, Pattern selection in coupled neurons under high-low frequency electric field, Heliyon 7 (1) (2021) e06132.
[29] M. Ge, Y. Yia, Y. Xu, L. Yang, Mode transition in electrical activities of neuron driven by high and low frequency stimulus in the presence of electromagnetic induction and radiation, Nonlinear Dyn. 515 (23) (2018).
[30] A. Fasano, A. Daniele, A. Albanese, Treatment of motor and non-motor features of Parkinson's disease with deep brain stimulation, Lancet Neurol. 11 (2012) 429–442.
[31] A. Lisi, M.T. Ciotti, M. Ledda, et al., Exposure to 50 Hz electromagnetic radiation promote early maturation and differentiation in newborn rat cerebellar granule neurons, J. Cell. Physiol. 204 (2) (2005) 532–538.
[32] S.C. Xu, Z. Zhou, L. Zhang, et al., Exposure to 1800 MHz radiofrequency radiation induces oxidative damage to mitochondrial DNA in primary cultured neurons, Brain Res. 1311 (2010) 189–196.
[33] R.R. Aliev, A.V. Panfilov, A simple two-variable model of cardiac excitation, Chaos Solitons Fractals 7 (1996) 293–301.
[34] M. Kohlhardt, M. Krause, H. Kübler, A. Herdey, Kinetics of inactivation and recovery of the slow inward current in the mammalian ventricular myocardium, Pfügers Arch. Eu. J. Phys. 355 (1) (1975) 1–17.
[35] M.S. Spach, The discontinuous nature of electrical propagation in cardiac muscle-consideration of a quantitative model incorporating the membrane ionic properties and structural complexities the ALZA distinguished lecture, Ann. Biomed. Eng. 11 (3–4) (1983) 208–261.
[36] S. Panahi, Z. Rostami, K. Rajagopal, H. Namazi, S. Jafari, Complete dynamical analysis of myocardial cell exposed to magnetic flux, Chin. J. Phys. 64 (2020) 363–373.
[37] A.S. Eteme, C.B. Tabi, A. Mohamadou, Long-range patterns in Hindmarsh-Rose networks, Commun. Nonlinear Sci. Numer. Simul. 43 (2017) 211.
[38] M.A. Nitsche, L.G. Cohen, E.M. Wassermann, A. Priori, N. Lang, et al., Transcranial direct current stimulation: state of the art 2008, Brain Stimul. 1 (2008) 206.
[39] D. Zipes, J. Jalife, Cardiac Electrophysiology: from Cell to Bedside, Elsevier, Amsterdam, 2013.
[40] F. Cordoni, L. Di Perso, Optimal control for the stochastic Fitzhugh-Nagumo model with recovery variable, Evol. Equ. Control Theory 7 (4) (2018) 571–585.
[41] V. Barbu, F. Cordoni, L. Di Perso, Optimal control of stochastic Fitzhugh-Nagumo equation, Int. J. Control 89 (4) (2016) 746–756.
[42] J. Ma, F.Q. Wu, C.N. Wang, Synchronization behaviors of coupled neurons under electromagnetic radiation, Int. J. Mod. Phys. B 30 (2016) 1650251.
[43] M. Lv, J. Ma, Multiple modes of electrical activities in a new neuron model under electromagnetic radiation, Neurocomputing 205 (2016) 375–381.
[44] C.N. Takembo, A. Mvogo, H.P. Ekobena, T.C. Kofane, Effect of electromagnetic radiation on the dynamics of spatiotemporal patterns in memristor-based neuronal network, Nonlinear Dyn. 95 (2) (2019) 1067–1078.
[45] A. Mvogo, C.N. Takembo, H.P. Ekobena, T.C. Kofane, Pattern formation in diffusive excitable systems under magnetic flow effects, Phys. Lett. A 381 (2017) 2264–2271.
[46] A.S. Tankou, C.N. Takembo, G.H. Ben-Bolie, P. Owona Ateba, Localized nonlinear excitations in diffusive memristor-based neuronal network, PLoS ONE 14 (6) (2019) e0214989.
[47] C.N. Takembo, A. Mvogo, H.P. Ekobena, T.C. Kofane, Wave pattern stability of neurons coupled by memristive electromagnetic induction, Nonlinear Dyn. 96 (2019) 1083–1093.
[48] J.A. Ruffner, N. Sperelakis, J.E. Mann Jr., Application of the Hodgkin-Huxley equations to an electric field model for interaction between excitable cells, J. Theor. Biol. 87 (1) (1980) 129–152.
[49] C.N. Takembo, P. Nyifeh, H.P. Ekobena, T.C. Kofane, Modulated wave pattern stability in chain neural networks under high-low frequency magnetic radiation, Physica A 593 (2022) 126891.