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Electromagnetic induction and radiation-induced abnormality of wave propagation in excitable media

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HIGHLIGHTS

- A new cardiac tissue model is proposed to describe the effect of electromagnetic induction and radiation.
- Magnetic flux variable is introduced to describe the effect of electromagnetic field.
- Memristor is used to bridge the membrane potential and electromagnetic field.
- Mechanism of electromagnetic radiation-induced heart disease is explained.

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ABSTRACT

Continuous wave emitting from sinus node of the heart plays an important role in wave propagating among cardiac tissue, while the heart beating can be terminated when the target wave is broken into turbulent states by electromagnetic radiation. In this investigation, local periodical forcing is applied on the media to induce continuous target wave in the improved cardiac model, which the effect of electromagnetic induction is considered by using magnetic flux, then external electromagnetic radiation is imposed on the media. It is found that target wave propagation can be blocked to stand in a local area and the excitability of media is suppressed to approach quiescent but homogeneous state when electromagnetic radiation is imposed on the media. The sampled time series for membrane potentials decrease to quiescent state due to the electromagnetic radiation. It could accounts for the mechanism of abnormality in heart failure exposed to continuous electromagnetic field.

1. Introduction

Spiral waves are often observed in chemical, physical and even biological systems [1–4], particularly, its emergence in cardiac tissue [5–7] can cause heart disease and even rapid death of heart suffering from arrhythmia [8]. For theoretical studies, many excitable models have been proposed to study the formation mechanism, stability and the suppression of spiral waves in excitable and oscillatory media [9–14]. In general, spiral waves can be reproduced on two-dimensional space described by reaction–diffusion equations, coupled oscillators on array, regular and/or small-world neuronal network [15–19]

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on one layer and even multi-layer neuronal networks [20]. For the chemical media and cardiac tissue, reaction–diffusion equations are often used to model the dynamical properties of wave propagation and emergence, furthermore, neuronal network with different types of topological connection are set for neuronal network so that the collective behaviors of neuronal activities can be discerned for disease prediction and understating. Spiral wave is also observed in neocortex and its biological function is believed to regulate the collective electrical activities like a pacemaker [21]. In fact, the emergence of spiral waves is associated with certain spatial coherence resonance [22–24], and noise [25,26], pacemaker-guided noise [27] can be helpful to enhance the coherence coherences and spatial regularity distribution. As a result, the dynamics of spiral wave in neuronal network has been extensively investigated [28–30]; readers can find more comments from the review and references therein [31], which claimed that spiral waves can be induced by breaking target waves or plane waves with defects.

However, the emergence of spiral waves in cardiac tissue is harmful for heartbeat and biological function. As a result, extensive studies have been carried out on cardiac models [32–35] to detect the dynamics of spiral waves in cardiac tissue, and thus many schemes [36–43] have been suggested to suppress the spiral wave, particularly, the pinned spiral waves [44–47] associated with heterogeneity in cardiac tissue. It is confirmed that continuous pulses, target waves can suppress the spiral wave and turbulence in the media and even the cardiac tissue. In fact, the formation mechanism for spiral wave in cardiac tissue could be that emitted waves from sinus node of the heart are blocked by defects, and broken target waves can be formed into spiral waves thus the normal wave propagation among the heart is destroyed. Indeed, emitted waves from the sinus node can regulate the heartbeat [48] by applying electrical signals on all myocardial cells to generate continuous relaxation and shrinkage of heart. As a result, the heartbeat can be perturbed and even terminated when the emitted continuous wave fronts are blocked, that the heart cannot bump enough blood to supply the body.

As it is well known, many realistic biological and even physical factors should be considered for neuronal and cardiac tissue models during the control of neuronal diseases and dynamical analysis. During the fluctuation of electrical activities and concentration of ions in cells, time-varying electromagnetic field can be induced when cells exposed or surrounded by electromagnetic field, as a result, the effect of electromagnetic induction should be considered. For example, Ref. [49] suggested magnetic flux can be used to model the effect of electromagnetic induction on membrane potential of isolate neuron, and it is further confirmed that electromagnetic field can induce multiple modes [50] in electrical activities which are consistent with the biological experiments [51,52]. Noise also plays important role on dynamical response of excitable media [24,53,54], appropriate noise intensity can enhance the spatial regularity and coherence of network though noise often can cause breakdown and disorder for electrical activities of neurons. The electrical activities of cardiac tissue can be regulated by the wave propagation emitted from the sinus node, and target-like wave is formed and propagated in the media of heart. The electrical activities of myocardial cells can be influenced by electromagnetic radiation. As a result, it is important to describe the effect of electromagnetic radiation on heart. Indeed, appropriate electromagnetic field can be induced in the cardiac tissue exposed to electromagnetic radiation.

In this paper, the effect of electromagnetic induction is considered in the cardiac tissue by using the variable of magnetic flux, the two-variable cardiac tissue model is improved for setting a new three-variable cardiac tissue model, electromagnetic radiation is imposed on the model to investigate the effect of electromagnetic field on wave propagation among cardiac tissue. Stochastic electromagnetic radiation is imposed on the model to detect the transition of electrical activities in cardiac tissue, it could be helpful to understand some potential mechanism for heart disease.

2. Model, scheme and discussion

As mentioned in Ref. [35], a simple two-variable model is proposed to describe the cardiac excitation and electrical activities, however, the physical effect for electromagnetic induction was not considered because time-varying electromagnetic field is induced during the period when the electrical signal and waves were emitted from the sinus node and propagated among the cardiac tissue. In fact, magnetic flux can be effective to describe the effect of electromagnetic induction and variation of electromagnetic field, and memristor is used to realize coupling and feedback on membrane potential of cells induced by time-varying electromagnetic field. The dynamical equations for the three-dimensional cardiac tissue of the new FitzHugh–Nagumo are described as follows

$$\begin{cases} \dfrac{\partial u}{\partial t} = -ku(u-a)(u-1.0) - uv - I_{st} - k_0\rho(\varphi)u + D_u\nabla^2 u \\ \dfrac{\partial v}{\partial t} = \left(\varepsilon + \dfrac{v\mu_1}{u+\mu_2}\right)[-v - ku(u-a-1.0)] \\ \dfrac{\partial \varphi}{\partial t} = k_1 u - k_2\varphi \end{cases} \tag{1}$$

$$\begin{cases} \rho(\varphi) = \dfrac{dq(\varphi)}{d\varphi} = \alpha + 3\beta\varphi^2 \\ i' = \dfrac{dq}{dt} = \dfrac{dq}{d\varphi}\dfrac{d\varphi}{dt} = \rho(\varphi)V = k_0\rho(\varphi)u \end{cases} \tag{2}$$

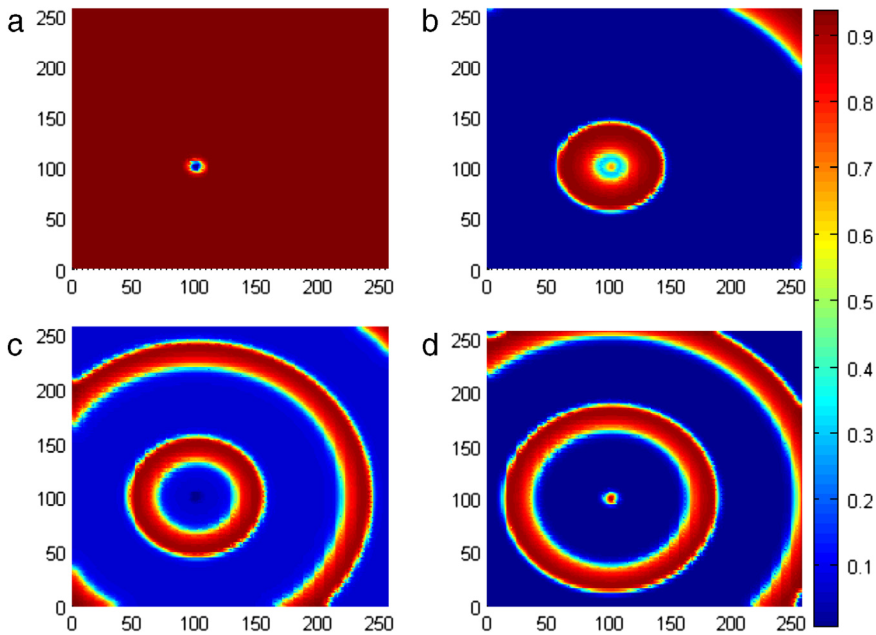

Fig. 1. Developed pattern in the cardiac tissue driven by local periodical forcing current I_0, and the center of area driving currents is selected as $(x_0, y_0) = (100, 100)$, $r \le 5$, at $I_0 = 0.23$, $\omega = 0.2$. For $t = 10$(a), $t = 60$(b), $t = 150$(c), $t = 200$(d), and no-flux boundary condition is used. Snapshots are plotted in color scale to describe the spatial distribution for membrane potentials u. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where u is the membrane potential, v represents the slow variable for current, I_{st} is the mapped transmembrane current from external forcing current, D_u measures the coefficient of diffusion. The nonlinear term $-ku(u-a)(u-1.0)-uv$ denotes the total transmembrane ionic current per unit area. The variable φ is the magnetic flux and used to describe the effect of electromagnetic induction during the fluctuation of electrical activities and ion concentration in cells. The nonlinear function $\rho(\varphi)$ is the memductance of memristor, which is used to described the modulation of time-varying electromagnetic field on membrane potential. The term $-k_0\rho(\varphi)u$ describes the induced current associated with electromagnetic induction. For simplicity and to be consistent with the previous works, the parameters are selected as, $a = 0.15$, $\mu_1 = 0.2$, $\mu_2 = 0.3$, $k = 8.0$, $\varepsilon = 0.002$, $k_0 = 1$, $k_1 = 0.2$, $k_2 = 1.0$, $\alpha = 0.1$, $\beta = 0.2$. In case of pattern formation and selection, the size of the media is set as 100×100, the space unit is calculated as 100/256, the diffusive coefficient D_u is set as 1. Firstly, a stable target wave is developed by applying periodical forcing current on local area of the media, which is used to produce a state in cardiac tissue occupied by target waves, it reads as follows

$$I = \begin{cases} I_0 \sin(\omega t), & r \le R \\ 0, & r > R \end{cases} \tag{3}$$

where I_0 and ω is the amplitude and angular frequency, R is the maximal radius of area driven by external forcing, r is the distance from the center of area. The original site of the media is set as (x_0, y_0), and it reads $r = [(x-x_0)^2 + (y-y_0)^2]^{1/2}$.

3. Numerical results and discussions

In the numerical studies, the Euler forward algorithm is used to calculate the time series for membrane potentials of the three-dimensional cardiac tissue with no-flux boundary condition being used, time step is set as $h = 0.02$. The initial values are selected quiescent state $u = 0$, $v = 0$, $\varphi = 0$. Target wave can be found in the cardiac tissue when continuous wave is emitted from the sinus node. At first, a stable target wave is developed by imposing continuous periodical forcing on local area of the media; the development of pattern is plotted in Fig. 1.

The results in Fig. 1 confirmed that stable target wave can be developed in the media with the increase of time. These states can be used to describe normal wave propagation in cardiac tissue controlled by emitted waves from sinus node. Furthermore, the sampled time series for some nodes are calculated to detect the periodicity of the wave emitting in the media, and the results are plotted in Fig. 2.

It is found in Fig. 2 that the sampled time series for membrane potential shows distinct periodicity when the media is occupied target wave completely. Extensive numerical results also confirmed that the external forcing current should be beyond certain threshold so that the media can be excited to propagate wave fronts among the media, and the discharge rhythm is also dependent on the media properties and angular frequency of the external forcing. For simplicity, the sampled

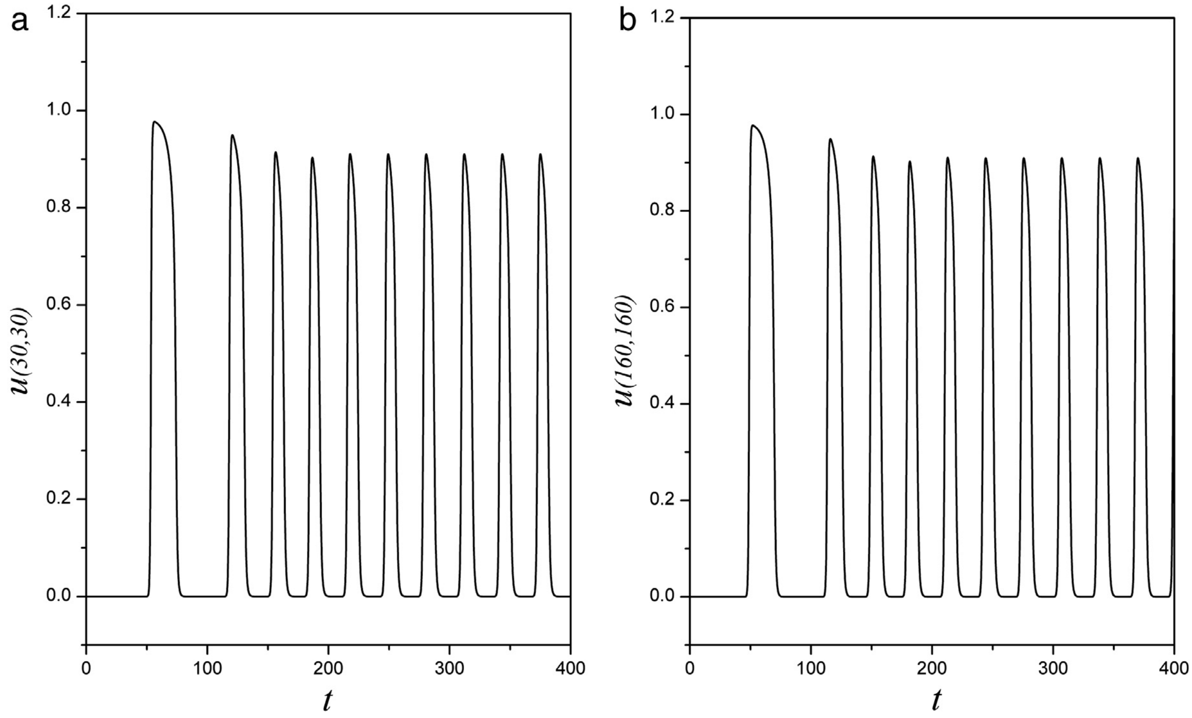

Fig. 2. Sampled time series for membrane potentials on different nodes, the parameters are set as $I_0 = 0.23$, $\omega = 0.2$, and no-flux boundary condition is used.

time series for node (90, 90) are calculated and FFT (fast Fourier transformation) is used to detect the power spectrum. The maximal power (peak) is denoted by S and its corresponding frequency is marked as ω_{peak}, $\Delta\omega$ is the width of angular frequency corresponds to the half peak ($\Delta\omega = \omega_2 - \omega_1$, ω_2, ω_1 finds the same half peak for power) in the power spectrum, then $S/(\Delta\omega/\omega_{\text{peak}})$ is calculated by changing different groups of diffusion coefficients and angular frequency, the results are plotted in Fig. 3.

It is found in Fig. 3 that appropriate diffusion coefficients and angular frequency can be detected to induce a strong target wave with higher power. Indeed, further calculating on $H = S/(\Delta\omega/\omega_{\text{peak}})$ can get SNR (signal-noise-ratio) as $10\log_{10}H$. The media will be occupied by target wave by applying appropriate periodical forcing on local area with appropriate diffusion coefficient, which is associated with excitability.

It is interesting to detect the effect of electromagnetic radiation on the stability of target wave. Considered the physical effect, electromagnetic radiation can change the distribution of magnetic flux, for simplicity, Gaussian white noise is imposed on the media as follows

$$\frac{\partial\varphi}{\partial t} = k_1 u - k_2\varphi + \xi(t), \tag{4}$$

where $\xi(t)$ is the Gaussian white noise, the statistical properties are defined as $< \xi(t) >= 0$, $< \xi(t)\xi(s) >= 2D\delta(t-s)$ and D is the noise intensity. The development of target wave is plotted when noise-like electromagnetic radiation is imposed on the media from the beginning and the results are shown in Fig. 4, furthermore, the sampled time series for membrane potential are calculated in Fig. 5.

The results in Fig. 4 find that target wave is suppressed in growth and wave propagation is blocked in a local area of the media when external electromagnetic radiation is imposed on the media completely. It is also found that sampled series from the target area (local area) in Fig. 5 show distinct periodicity while the sampled time series from other area decrease to death in oscillating behavior, which means the area becomes homogeneous. Furthermore, we also checked the case when electromagnetic radiation is imposed local area began from the node (150, 150) with a maximal radius $R_1 = 50$, and the results are plotted in Fig. 6.

It is interesting to observe the emergence of spirals induced by breaking the target wave in a local area; as a result, the media is controlled by the spirals with distinct periodicity. And the formed spirals are driven to drift to the boundary of the media by continuous target waves in the local area. Then the sampled time series for membrane potentials are tracked in Fig. 7.

With the increase the time, spirals began to occupy the media and thus the media shows distinct periodicity, which is carefully adjusted during the competition and collision between spirals and target waves in the media. Furthermore, a stable

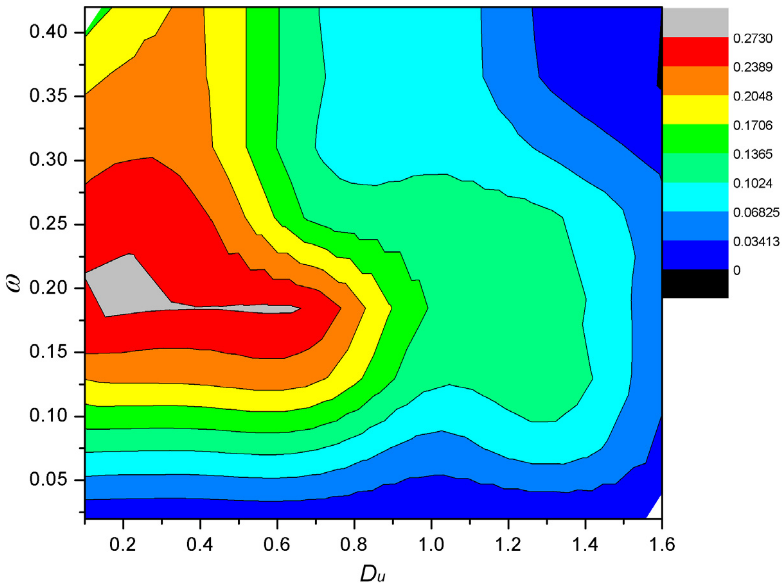

Fig. 3. Distribution for power-frequency on the phase space for diffusion coefficient D_u vs. angular frequency ω of external forcing current at amplitude $I_0 = 0.23$. The snapshot is plotted in color scale to describe the diversity for $S/(\Delta\omega/\omega_{\text{peak}})$, time series for membrane potentials are sampled from node (90, 90). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

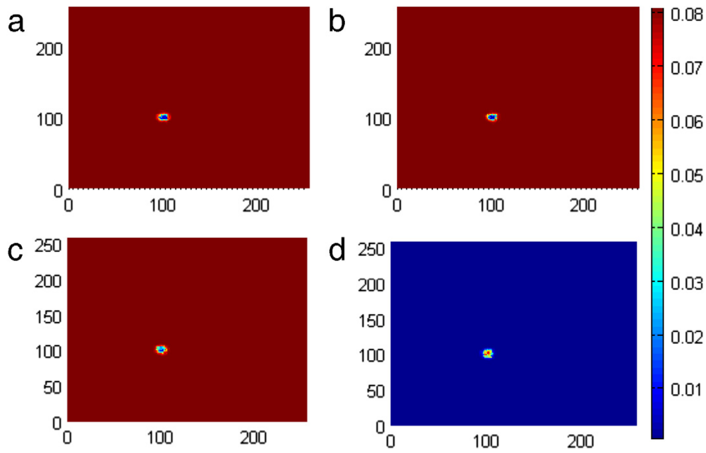

Fig. 4. Developed pattern in the cardiac tissue driven by local periodical forcing current I_0 by imposing external electromagnetic radiation on the media completely, this intensity is set as $D = 10$, at $I_0 = 0.23$, $\omega = 0.2$. For $t = 10$(a), $t = 60$(b), $t = 150$(c), $t = 200$(d), and no-flux boundary condition is used. Snapshots are plotted in color scale to describe the spatial distribution for membrane potentials u. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

target wave is triggered as initial state with a transient period about 200 time units, then external electromagnetic radiation is imposed on the media completely, the development and transition of target waves are calculated in Fig. 8.

Similar to the results in Fig. 4, the results in Fig. 8 confirmed that the developed target wave can be suppressed in a local area, thus target wave cannot be propagated outside. Therefore, the excitation from the wave front of target wave is blocked. As a result, most area of the media except a local area close to the target source is suppressed to be quiescent state; it means that the signal propagation of electrical activities are terminated. Furthermore, the sampled time series for membrane potentials are tracked in Fig. 9.

It is found in Fig. 9 that the time series for membrane potentials sampled from some nodes decrease to quiescent state with the increase of calculating time when external electromagnetic radiation is imposed on the media occupied by target wave. As a result, the oscillating behavior of electrical activities is suppressed and the heartbeat is terminated. The potential mechanism could be that large or strong electromagnetic radiation depolarizes the media and the excitability is suppressed greatly. It is different from the breakup of spiral wave-induced disorder of heart disease associated with tachycardia and ventricular fibrillation. It also indicates that heart function can encounter abnormality when it is exposed

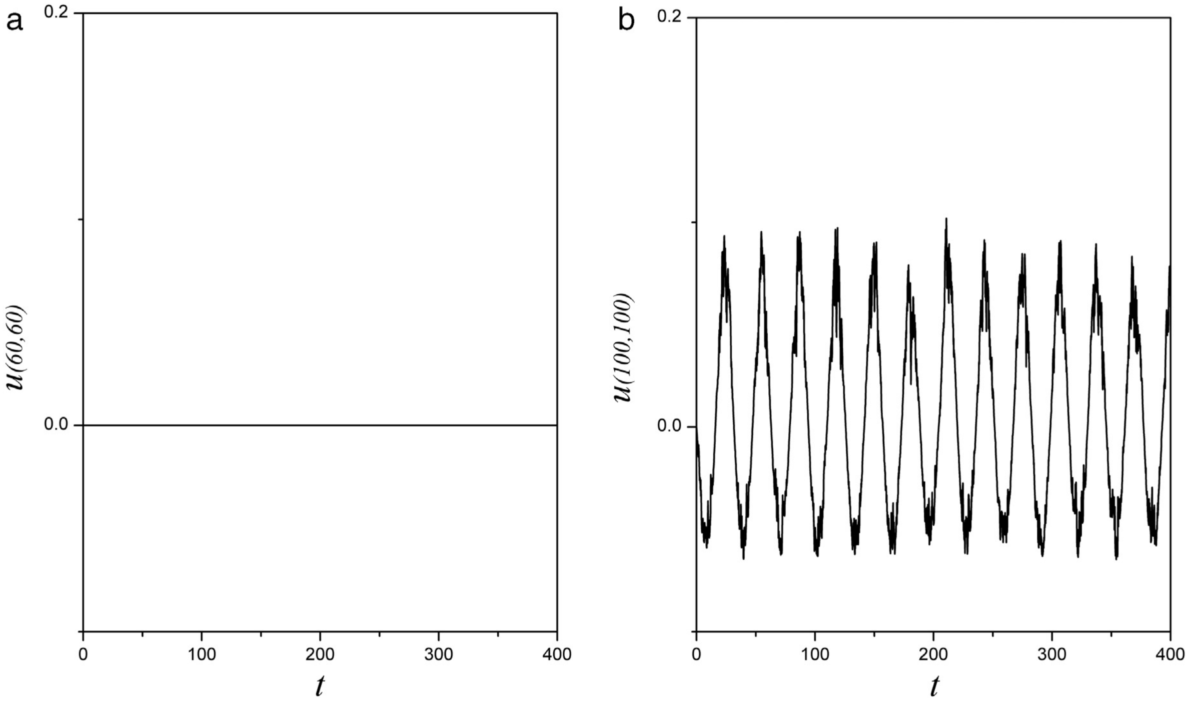

Fig. 5. Sampled time series for membrane potentials on different nodes are calculated, the parameters are set as $I_0 = 0.23$, $\omega = 0.2$, and no-flux boundary condition is used.

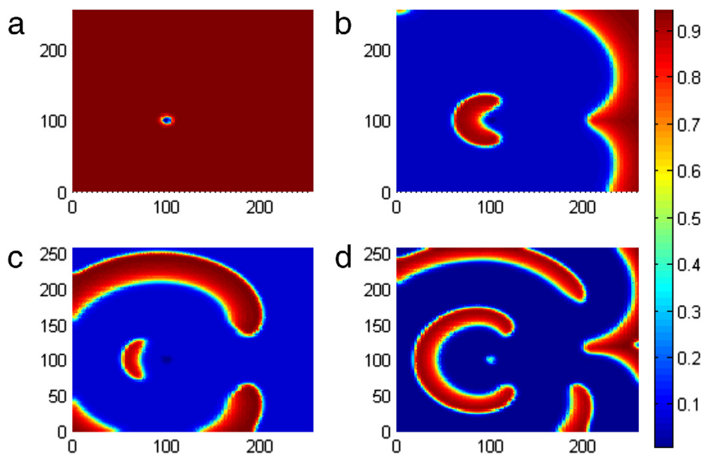

Fig. 6. Developed pattern in the cardiac tissue driven by local periodical forcing current I_0 and external electromagnetic radiation is imposed on a local area expanded from the node (150, 150) with a maximal radius $R_1 = 50$, the radiation intensity is set as $D = 10$, at $I_0 = 0.23$, $\omega = 0.2$. For $t = 10$(a), $t = 60$(b), $t = 150$(c), $t = 200$(d), and no-flux boundary condition is used. Snapshots are plotted in color scale to describe the spatial distribution for membrane potentials u. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to electromagnetic field with strong radiation intensity. In fact, similar results are approached in Ref. [55] found that the instability of scroll waves which appears in three-dimensional excitable systems in the low excitability regime can be tamed by feeding spatiotemporal stochastic fluctuations into one of the parameters, which controls the excitability of the system. For our proposed model, stochastic fluctuations into the magnetic flux can also control the memductance of memristor thus the dynamical response of the model is changed, and the wave propagation is suppressed and blocked.

In a summary, magnetic flux can be effective to describe the changes of electromagnetic field. As a result, magnetic flux is introduced into the simplified cardiac tissue model and the memristor, whose memductance is dependent on the initial inputs, is used to realize feedback coupling on membrane potential of cell. The external electromagnetic radiation is thought to change the distribution of magnetic flux and then the electrical activities can be adjusted. It is found in this new model that electromagnetic radiation can suppress the normal electrical activities and heartbeat can be perturbed.

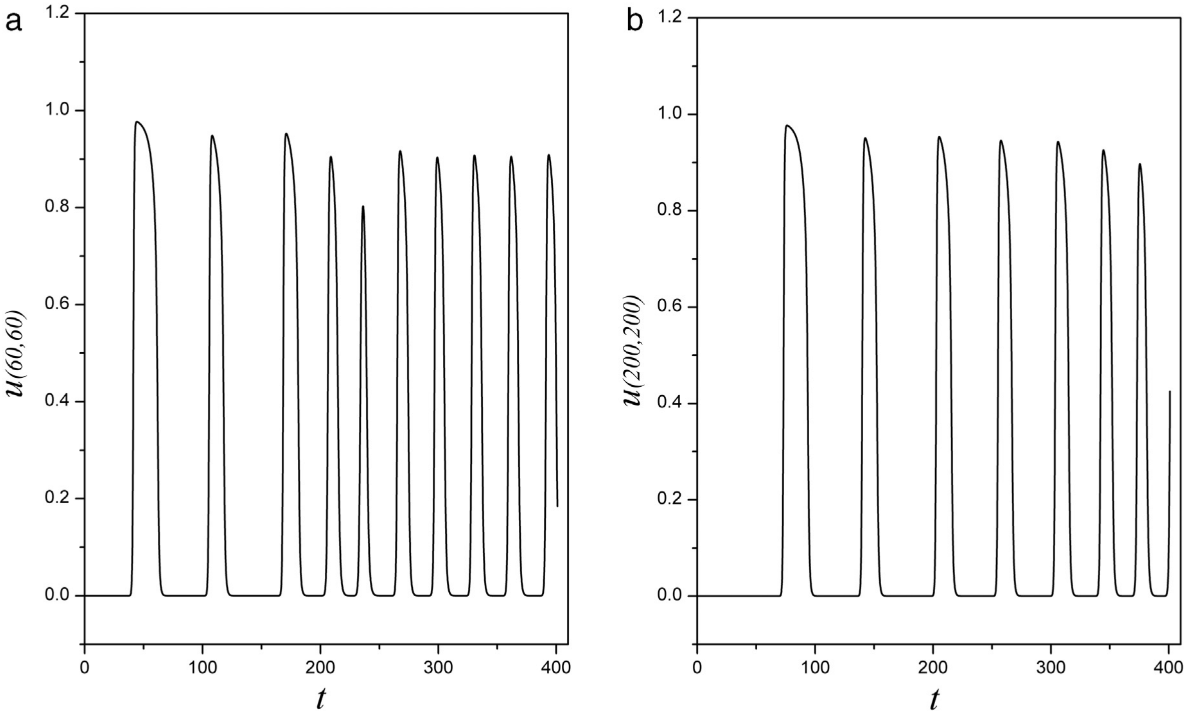

Fig. 7. Sampled time series for membrane potentials on different nodes, the parameters are set as $I_0 = 0.23$, $\omega = 0.2$, and no-flux boundary condition is used.

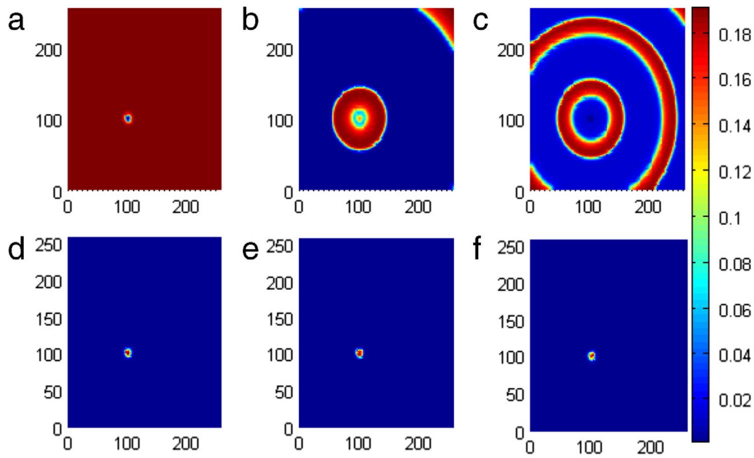

Fig. 8. Developed pattern in the cardiac tissue driven by local periodical forcing current I_0 and external electromagnetic radiation is imposed on a local area expanded from the node (150, 150) with a maximal radius $R_1 = 50$, within a transient period about 200 time units, radiation intensity is set as $D = 10$, at $I_0 = 0.23$, $\omega = 0.2$. For $t = 10$(a), $t = 60$(b), $t = 150$(c), $t = 200$(d), $t = 210$(e), $t = 300$(f), $t = 400$(g), and no-flux boundary condition is used. Snapshots are plotted in color scale to describe the spatial distribution for membrane potentials u. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

An improved cardiac model, which the effect of electromagnetic induction is described by magnetic flux, is proposed to study the transition of electrical activities in cardiac tissue exposed to electromagnetic field. For a normal heart, continuous wave propagation is helpful for shrinkage and relaxation of heart. However, our results confirmed that electromagnetic radiation can suppress the wave propagation of target wave developed from the sinus node, that is to say, electrical signal and wave emitting just can be kept alive in a local area while most of the area of the cardiac tissue is blocked to receive any electrical signal. As a result, the shrinkage and relaxation of heart is suppressed, furthermore, no enough blood can

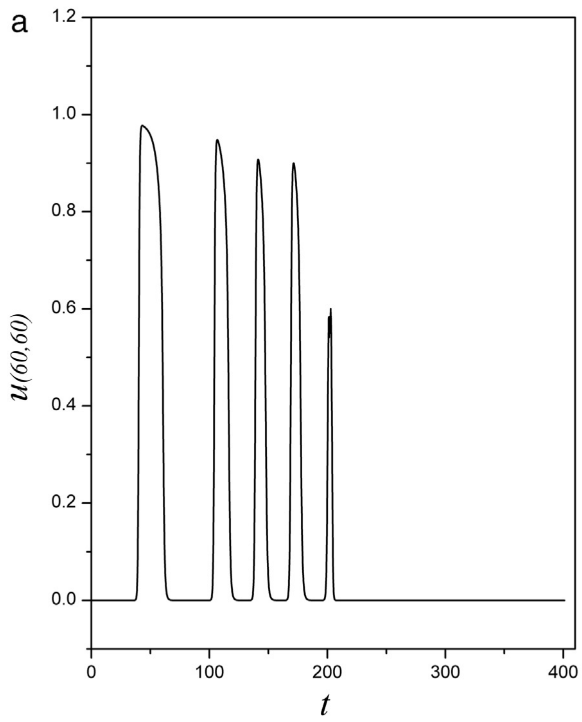

Fig. 9. Sampled time series for membrane potentials on different nodes, the parameters are set as $I_0 = 0.23$, $\omega = 0.2$, and no-flux boundary condition is used.

be pumped to supply the body, heartbeat is suppressed and collapse of body occurs. It tells us that prevention against of electromagnetic radiation is important and helpful for our health in heart.

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