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Dynamics of a spiral pair source and its interaction with plane waves

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ABSTRACT

Spiral pair creation and dynamics is a widely occurring phenomenon in nature. It can appear in the heart tissue, causing severe arrhythmia, known as a figure-eight reentry. We consider the appearance of a spiral pair source, its minimal strength for survival, and the possible results of its interaction with a plane wave. In particular, its ability to outlast such an encounter is of interest. We also consider the question of exposing the source to a train of pulses, in terms of the frequency and angle of encounter. Results show different regimes of behavior, e.g. source annihilation, motion of the source away from, or towards the origin of the plane waves, its breaking and multiplication. Relevance of these results to heart arrhythmia and their possible cancellation by external pacing are briefly discussed.

1. Introduction

Heart tissue is an excitable medium, therefore under normal condition the tissue can support the passage of only a single action potential (AP) pulse, to be followed by a refractory period during which no additional AP pulse can be transmitted. In heart dysfunction situations, however, an "ectopic" spiral, or spiral pair source happens to appear at some location in the heart. Such a source repeatedly emits pulses which interfere with the regular functioning of the heart, and can lead to severe and even deadly malfunctions [1–3]. Ectopic spirals in the heart are commonly associated with different *reentry* arrhythmias among which the arrhythmia caused by a spiral pair is specified as a figure-eight reentry [4,5]. Application of local electric impulses from an implantable devise (pacing) is widely used to terminate reentry—but this treatment is not always successful. It is known that pacing to suppress *single* spirals causing ventricular tachycardia (VT) may lead to an adverse effect of spiral multiplication which results in even the more dangerous phenomenon of ventricular fibrillation (VF) [6,7]. The necessary conditions for the success of such pacing are poorly understood.

A typical example of a reentrant arrhythmia is associated with a spiral rotating around a non excitable anatomical obstacle ("anatomical reentry"). Moreover, ectopic spirals can arise without a specific anatomical circuit or abnormal myocardium. These spirals typify a so-called "functional reentry", and can occur in regions with induced excitability gradients, where circumstances arise for unidirectional functional block, and rotating pulse motion [3]. Pacing of a single functionally induced spiral has been studied both experimentally and in computer simulations (see e.g. [6–11]), showing that the final effect of an externally applied stimulus on spiral wave activity may result in either termination of the activity, in multiplication with the establishment of figure-eight reentry, in the change in the position of the spiral core, or in no effect whatsoever. The occurrence of each one of these responses depends on the stimulus timing as well as on the electrode size and position [6]. The pacing of anatomical figure-eight reentry caused by a spiral pair rotating around two distinct anatomical obstacles was studied in Ref. [10]. In a crucial realistic difference from previous studies of such systems, the pacing site was placed away from the reentry circuit. It was particularly shown that with such off-circuit pacing, the existence of inhomogeneity in the reentry circuit is essential for successful termination of tachycardia under certain conditions. Analogous off-circuit pacing of a *functional* figure-eight reentry was also numerically investigated [11].

In the present work we consider the appearance of an ectopic spiral pair source, its minimal strength for survival, and its ability to outlast an encounter with a regular AP arising from the natural, or an implanted pacemaker. Next, we take up the problem of getting rid of such a source by exposing it to a train of pulses, and treat the frequency of the latter and the angle of encounter as parameters

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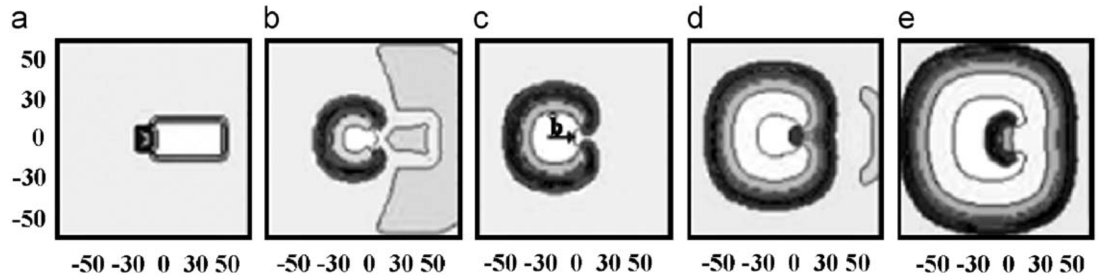

Fig. 1. Time evolution of an ALP with $\hat{b}=\hat{x}$ inducing a spiral pair. $\Delta t=0.1$, $\Delta x=\Delta y=2$: (a) $t=10$; (b) $t=140$; (c) $t=190$; (d) $t=265$; and (e) $t=355$.

to check the regions where source annihilation is possible. We also show that off-circuit pacing of a spiral pair can lead to its breaking and consequent multiplication.

2. The method of creating a unidirectional propagating pulse and a source of spiral pairs

For the sake of completeness we remind here our method [12–15] of creating a unidirectional propagating pulse and a source of spiral pairs, and define the latter's direction. We consider the following FitzHugh–Nagumo (FHN) system [16]

$$\frac{\partial v}{\partial t}=D\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)v+v(v-a)(1-v)-w+\delta(t)I(x,y)$$
$$\frac{\partial w}{\partial t}=\varepsilon(v-dw) \quad (1)$$

where all the variables are in dimensionless units. Here, v is the AP, while w is the refractivity, an inhibitory variable, $\delta(t)I(x,y)$ is an input current. The constant D, and ε are the diffusion constants, and the ratio between the fast and the slow time constants, respectively. The constant a controls the excitability of the medium. Thus, for $a\leqslant 0$ the medium is oscillatory (depicting, e.g. the sinus node of the heart). As $a>0$ increases, the excitability of the medium decreases until for a value above a certain critical value a_c, excitability is completely lost. The constant d controls the shape of the AP profile (see e.g. [17] and references therein). We use $a=0.12$ (excitable medium), $D=0.2$, $d=3$, $\varepsilon=0.005$ throughout. The spatial contour of the input current consists of two adjacent rectangles of dimensions $c_1\times b_1$ and $c_2\times b_2$. The small rectangle $c_1\times b_1$ is located to the left of the other, see Fig. 1a. The current amplitudes are h_1, above threshold, and h_2, below threshold, respectively [15]. We use $c_1=12$, $b_1=10$, $c_2=30$, $b_2=60$, $h_1=0.2$ and $h_2=0.155$, throughout, except for Section 4 where c_1, b_1, c_2, and b_2 are varied in order to find the threshold for spiral pair generation.

To show the creation process of a spiral pair generator let us consider the time evolution of the system presented in Fig. 1. The asymmetric initial current in Fig. 1a generates a unidirectional propagating arc-like pulse (ALP) (Fig. 1b), whose free ends start curving in opposite directions around two distinct centers, i.e. they transform into tips of two counter-rotating spirals (Fig. 1c). The rotation of these spiral tips continues until their arms collide and partially annihilate (Fig. 1d). As a result, two structures appear simultaneously: an outwards moving concentric pulse and an ALP (Figs. 1d and e). The ALP in Fig. 1e, being similar to the one in Fig. 1b, causes a repetition of the entire process, resulting in the appearance of two new structures, one concentric, and the other an ALP, etc.

The ALP is an oriented, mirror symmetric object, whose orientation can be specified by a unit vector $\hat{b}$ situated along the symmetry axis, pointing from the convex apex of the ALP towards the eventual contact point of its arms (see Fig. 1c).

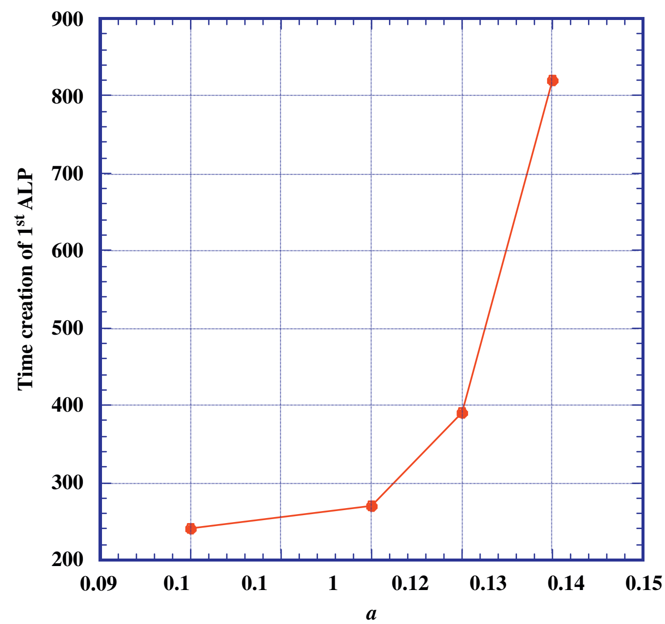

Fig. 2. The time of creation of the first ALP as a function of a.

3. Threshold of ALP strength for creating a spiral pair

In order to find the minimal strength of an ALP above which it does not die out but rather creates a spiral pair, several simulations were carried out with initiating pulses of various sizes c_1 and b_1, allowing the creation of a spiral pair. The pulses were allowed to develop until the two arms touched each other, creating the first ALP. At this time the ALP strength, S, where $S=\int v\cdot dx\,dy$, was measured. It was found for the parameter $a=0.12$ in Eq. (1), that at strengths larger than $S_c=7$ the source does not decay and continues to generate additional spiral pairs, while for the $S<S_c$ the source decays and finally dies out. Since the inhibition here is present ($w\neq 0$), this value of S_c is larger than the strength needed for a quiescent medium ($w=0$) [18,19]. It was also found that varying a in the range where an ALP is created gives rise to changing time of creation of the ALP, but does not affect the value of S_c. Fig. 2 presents the appearance time of the 1st ALP as a function of a. It is seen that when a increases (i.e. the system becomes less excitable) the time to create the first ALP rises too.

4. Interaction between an ALP and a plane wave

The aim here was to study the interaction between the ALP and a single moving plane wave. We denote the interaction configuration by $(\hat{b},\hat{v})$ where $\hat{b}$ is the direction of the spiral pair (ALP), and

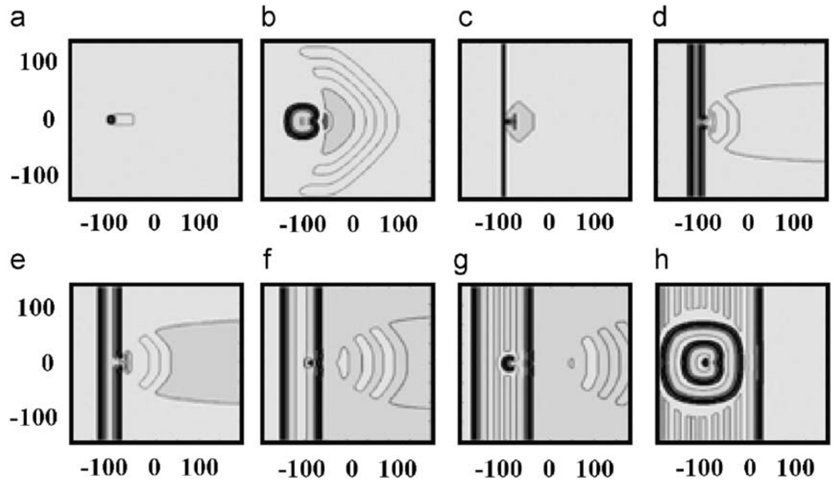

Fig. 3. The interaction between an ALP (with $\hat{b}=\hat{x}$) introduced at $x=-50$ and an external plane wave introduced at $x=-75$: (a) $t=10$; (b) $t=225$; (c) $t=295$; (d) $t=380$; (e) $t=430$; (f) $t=555$; (g) $t=670$; and (h) $t=1185$.

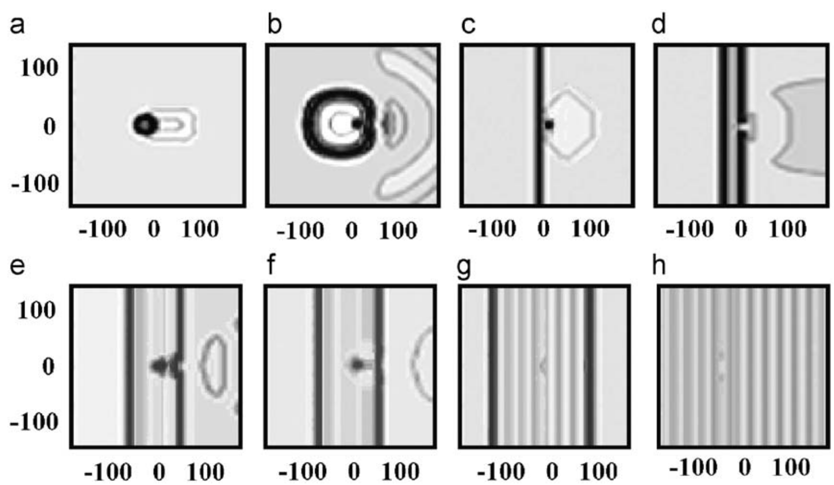

Fig. 4. The interaction between an ALP ($\hat{b}=\hat{x}$) introduced at $x=-50$ and a plane wave introduced at $x=-58$: (a) $t=30$; (b) $t=225$; (c) $t=285$; (d) $t=360$; (e) $t=465$; (f) $t=560$; (g) $t=580$; and (h) $t=1605$.

$\hat{v}$ is the propagation direction of the plane wave. The two main interaction possibilities discussed in this section are: (a) same direction, i.e $(\vec{b},\vec{v})=(\hat{x},\hat{x})$ or $(-\hat{x},-\hat{x})$ and (b) opposite direction, $(\hat{x},-\hat{x})$ or $(-\hat{x},\hat{x})$. Other possibilities are discussed in Section 7. Generation of a single "pure" ALP is carried out as follows: an ALP with $\hat{b}=+\hat{x}$ is created (at $x=-50$, Fig. 3a and b) by the first two steps of the previously described procedure. At time t_s, the first instant when the ALP strength exceeds S_c (270 time units in Fig. 3), all elements, apart from the ALP source itself, are removed, making this ALP the new "initial condition" (including the inhibitor). The ALP interaction with a single plane wave is now considered. Two cases with different time intervals between the creation of the ALP and the collision are examined. In the first case this interval is relatively long, while in the second, it is short. In the first case, a plane pulse $\delta(t-t_s)I_1(x=-75)$ is introduced to the left of the ALP (Fig. 3c). The plane pulse splits into two plane waves propagating in opposite directions, so that the ALP interacts with the right propagating wave. This plane wave meets the ALP (the case here is the $(\hat{x},\hat{x})$ variety), and annihilates it. As a result, a gap is created in the plane wave at the position of interaction. Two free ends thus appear (Fig. 3d), and begin to rotate (Fig. 3e) until they touch each other, and another ALP is created. The rotation is obviously induced by the retarded motion of the ends with respect to the (right) propagation of the plane wave.

If the gap in the plane wave exceeds some critical value (to be discussed in the next paragraph), a new ALP source is produced, and generates more spiral pairs (see Figs. 3g and h).

Fig. 4 presents the second case where a similar process is considered with a shorter distance from the ALP to the plane wave (Fig. 4c), which starts at $x=-58$. In this case, the gap in the plane wave, produced during interaction, is less than the critical value $(S<S_c)$, and the new ALP eventually disappears (Figs. 4g and h).

In the simulations described above the orientation of the ALP was chosen as $\hat{b}=\hat{x}$. In Fig. 5 we present results of simulations with oppositely orientated ALP, i.e. $\vec{b}=-\hat{x}$. The initial system evolves into an ALP, and a plane wave is introduced at $x=-90$ (Fig. 5a). Annihilation takes place during collision, *at the contact sites*, so that the ring and the plane wave merge, creating a bulge in the plane wave, and a small free wave remnant in the middle (Fig. 5b). This remnant develops into a new ALP (Figs. 5c and d), if its strength is larger than S_c. If the plane wave is introduced too close to the initial ALP, so that the remnant is smaller than the critical value $S<S_c$, it will decay and disappear.

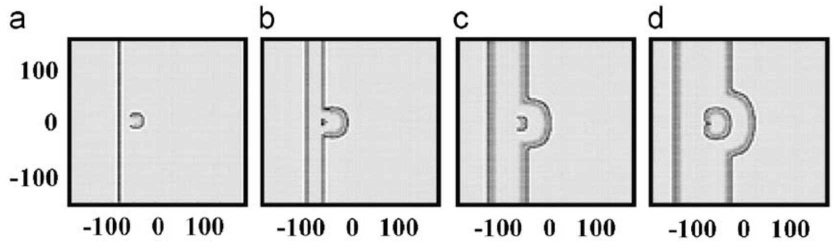

Fig. 5. The interaction between an ALP ($\hat{b} = -\hat{x}$) introduced at $x = -50$ and a plane wave introduced at $x = -90$: (a) $t = 105$; (b) $t = 240$; (c) $t = 360$; and (d) $t = 490$.

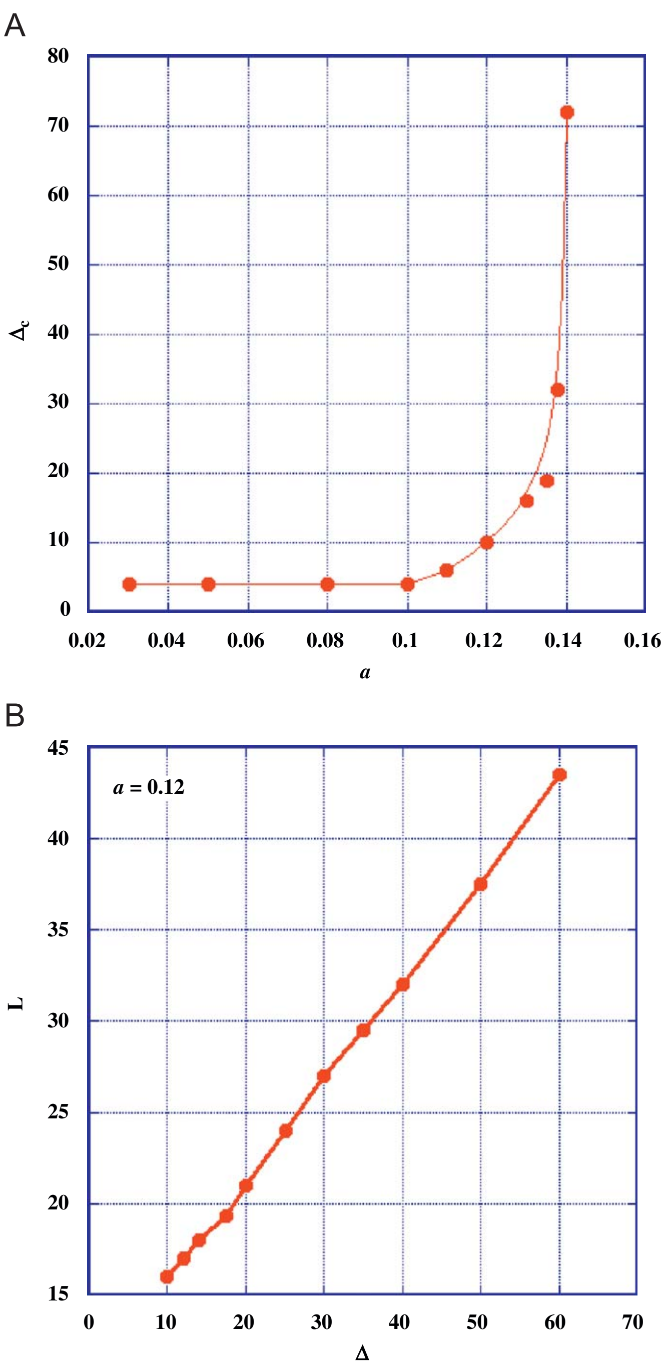

Fig. 6. (A) The threshold gap width in a plane wave allowing the creation a viable ALP, as a function of a. (B) The distance from the plane wave to the "healing" position as a function of Δ with $\Delta > \Delta_c$, for constant $a = 0.12$.

5. The threshold of the width of a gap in a plane wave for creating an ALP

As seen in Figs. 3d and e and 4d, the collision between the ALP and a plane wave of a common direction creates a gap in the plane wave, producing two free edges. These begin to rotate in the opposite direction to the translational motion of the plane wave and, if the gap is wide enough, another ALP will be created (Figs. 3d–f). In order to find the condition for a minimal gap width under which a new ALP is created, gaps of different width sizes Δ were artificially cut in propagating plane waves. Results show that the system can "heal" the gap at a distance L, if $\Delta < \Delta_c$, where L is the perpendicular distance at which the two ends meet. The plane wave will now move on intact. For $\Delta > \Delta_c$ on the other hand, another viable ALP will be created, leading to the generation of additional spiral pairs. For the set of parameters used here $\Delta_c = 10$ length units. Changing the parameter a in Eq. (1), the critical value Δ_c also changes. The value of Δ_c is the smallest value of Δ below which no viable ALP can exist. Note that for values of Δ smaller than Δ_c, the small remnant can develop into a double spiral form, the arms of the latter close too early to create an additional ALP, so only a single outgoing wave is developed (no source).

For a large range of a values, Δ_c is almost constant with a steep rise near $a = 0.14$ (Fig. 6A). As a increases, the system becomes less excitable (see e.g. [17]), thus proceeding slower. The tips rotations become even slower than the arms joining motion, thus requiring a wider gap for the creation of a viable ALP. Fig. 6B describes the change of L with Δ ($\Delta > \Delta_c$) for a constant $a = 0.12$. The resulting trend is almost linear. It is not absolutely linear since, for increasing ALP size, the contact of the arms occurs at a different position.

6. Interaction between an ALP and a train of plane waves

The purpose of the present series of simulation is to investigate the interaction between the ALP and a train of equidistant plane waves in order to check whether the ALP can thus be annihilated. Simple simulations of such a procedure were done in Ref. [10]. As will be seen, the results are crucially dependent (as can be anticipated) on the frequency of the wave train. Firstly, an ALP with $\hat{b} = -\hat{x}$ was created at $x = -50$ and $y = 0$. Starting at $t = 0$, successive plane waves are generated at $x = 0$, every 75 time units, which is smaller than the generation period of new ALP (see below). Fig. 7 presents various stages of interaction between the ALP and the wave train. Since the initial distance between the ALP and the first incoming wave is large enough, the ALP before interaction, manages to produce a set of concentric waves (and new ALP's), whose generation period is measured to be about 240 time units. When the plane waves encounter the system of concentric waves (Figs. 7b and c) the latter are annihilated one by one, eventually leaving the "bare" ALP (Fig. 7c). When the next plane wave encounters the ALP, a gap opens in the wave (Fig. 7d), and its two free edges rotate until they touch each other, creating another ALP (Fig. 7e). In the present case, however, its strength is smaller than the previous ALP, and the succession of interactions of this kind eventually causes a decrease of ALP

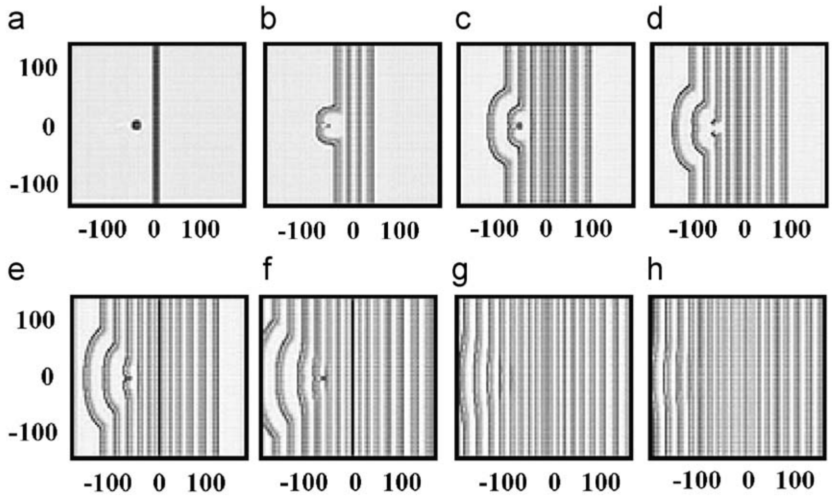

Fig. 7. The interaction between an ALP with $\hat{b} = -\hat{x}$, and a train of external plane waves moving in $-\hat{x}$ direction, and a period of 75 time units: (a) $t = 30$; (b) $t = 245$; (c) $t = 570$; (d) $t = 660$; (e) $t = 830$; (f) $t = 1050$; (g) $t = 1715$; (h) $t = 1940$.

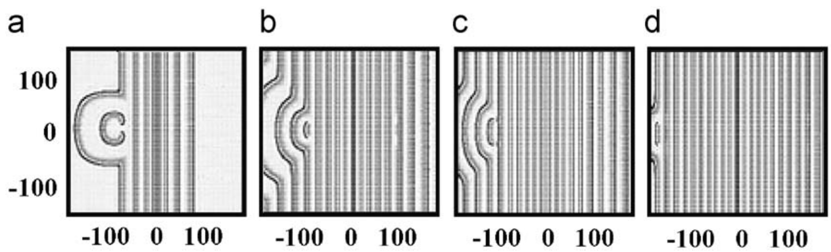

Fig. 8. The interaction between an ALP with $\hat{b} = +\hat{x}$, created at $x = -50$, and a train of plane waves generated at $x = 0$, and a period of 75 time units: (a) $t = 495$; (b) $t = 1370$; (c) $t = 1890$; (d) $t = 3470$.

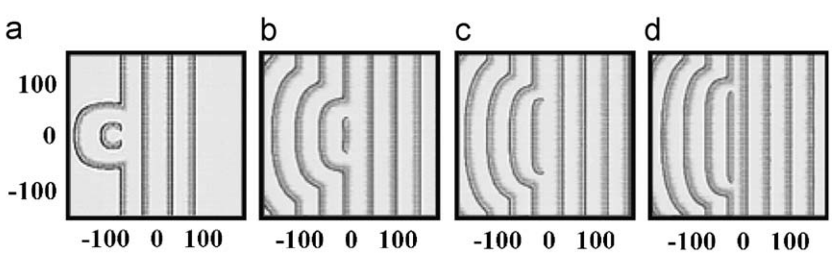

Fig. 9. The interaction between an ALP with $\hat{b} = +\hat{x}$ and a train of plane waves moving in $-\hat{x}$ direction, and a period of 250 time units: (a) $t = 465$; (b) $t = 10965$; (c) $t = 12780$; (d) $t = 13300$.

strength below the threshold value S_c, leading to its disappearance (Figs. 7g and h).

For an ALP with $\hat{b} = +\hat{x}$, the set of parameters, including the time interval between consecutive plane waves, was the same as for $\hat{b} = -\hat{x}$. In this case the ALP does not disappear. The simulation indicates that the ALP is rather pushed to the left by the wave train, as can be seen in Fig. 8.

The next simulations set was similar to the one described in Fig. 7 except that the time interval between consecutive plane waves was 250 time units. Now the time interval is long enough to allow the ALP to grow in amplitude, the gap being above the threshold. As a result, each time the ALP meets the plane wave, a new ALP is generated.

For the case depicted in Fig. 8, with a time interval of 250 between consecutive waves, the only concentric wave surrounding the ALP in this case is annihilated by a plane wave in such a way that the internal small part which remains from the ALP has two free edges which begin to rotate but do not succeed in completing this task before meeting the next plane wave. This time, however, the encounter occurs closer to $x = 0$, and the distance between the free edges is longer (see Fig. 9).

For the next simulation set, a time interval of 600 time units was chosen between the plane waves. In this case, the ALP increased to such an extent that several arms developed into rings surrounding it (see Fig. 10b). When the plane waves encounter these rings the position of contact is eventually transferred to the origin of the plane wave generating position. There, in subsequent interactions (see Figs. 10c and g), the rings are converted into free edges, which start rotating, thus creating more ALP sources (breaking and multiplication). The system eventually becomes complex (Figs. 10d–f, h). For this value of the time interval, the behavior of both $\hat{b} = +\hat{x}$ and $-\hat{x}$ ALPs is similar.

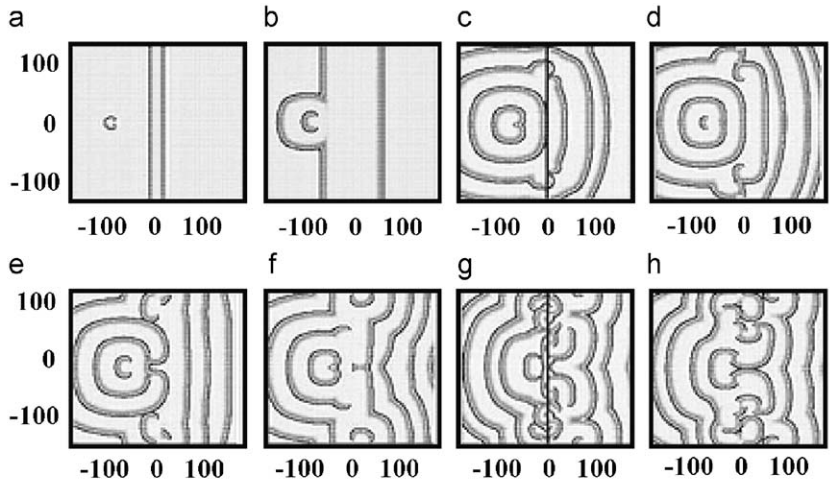

Fig. 10. The interaction between an ALP with $\hat{b} = +\hat{x}$ and a train of plane waves moving in $-\hat{x}$ direction, and a period of 600 time units: (a) $t = 90$; (b) $t = 436$; (c) $t = 2365$; (d) $t = 2775$; (e) $t = 4045$; (f) $t = 2545$; (g) $t = 12035$; (h) $t = 12365$.

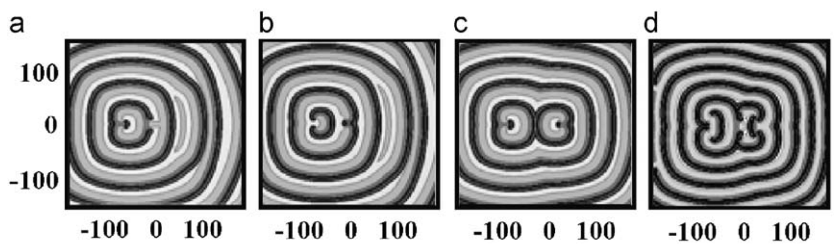

Fig. 11. The interaction between an ALP ($\hat{b} = +\hat{x}$) created at $x = -50$, $y = 0$ and a train of target waves originated at $y = x = 0$, and a period of 600 time units: (a) $t = 1805$; (b) $t = 1980$; (c) $t = 4210$; (d) $t = 20000$.

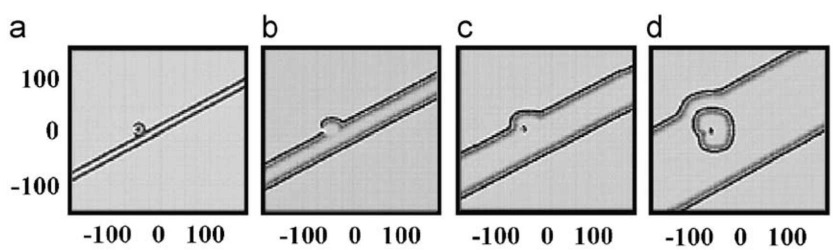

Fig. 12. The interaction between an ALP with $\hat{b} = +\hat{x}$, and a train of plane waves introduced along the line $y = (\pi/10)x + 4$: (a) $t = 75$; (b) $t = 175$; (c) $t = 280$; (d) $t = 570$.

In addition, we have examined the case where, instead of plane waves, we used a point source pacer to generate target waves at the origin. Results obtained are similar to those of the plane waves. A specific case is presented in Fig. 11, where the ALP is created at $(-50, 0)$, the pacer operates at $x = y = 0$ and the wave train period is 600 time units.

7. Interaction between an ALP and train of plane waves propagating at different angles

The results presented in the previous sections were obtained for collinear directions of motion of the ALP and the plane waves. Three main types of behavior were observed depending on the time interval between the subsequent plane waves: (i) for a short time interval of about 75 time units the plane waves either destroyed the ALP pointing in the same direction as that of the waves (Fig. 7), or pushed out the oppositely directed ALP (Fig. 8); (ii) for an intermediate time interval of about 250 time units, the ALP of the same direction as the that of waves, always remains, while the oppositely directed ALP moves to the origin of the plane waves (Fig. 9); (iii) for a long time interval of about 600 time units both "positive"($\hat{b} = +\hat{x}$) and "negative"($\hat{b} = -\hat{x}$) ALPs behave in a complex way (Figs. 10 and 11).

An additional set of simulations was performed in which the plane waves were directed at various angles with respect to the x-axis. Generally, all types of behavior presented above were observed, but the characteristic time intervals were essentially different. A new effect was observed when the plane waves contacted the ALP at small angles: the ALP here changes its direction and propagates in another direction, imposed by the plane waves. A specific case is shown in Fig. 12 where the plane waves strikes the ALP at the angle of $\pi/10$, resulting in turning the ALP into a different direction.

8. Conclusion

In the framework of the FHN system it was shown that:

1. An ALP is a source of spiral-pairs if its strength is higher than a certain threshold. The value of this threshold does not change with the excitability controlling parameter a. However, at different a the ALPs are created at different times.
2. The ALP is an oriented entity which can encounter a plane wave moving either in the same direction as its orientation, in an opposite direction or in an inclined direction. The outcome of the interaction depends on the time elapsed between the ALP creation and the instant of collision, since this determines the size to which the ALP has grown.
   (a) The collision in opposite directions leads to the disappearance of the ALP, and the creation of a gap in the plane wave. If the gap width is above a certain threshold, a new ALP is created by the rotation of the free edges of the moving plane wave. Otherwise, the gap is healed. The critical gap width does not change with the excitability parameter a until the latter approaches the excitability limit where this width increases sharply.
   (b) The collision in a common direction leads again to the disappearance of the ALP, but here the plane wave acquires a bulge, and in addition two gaps are opened in it, separated by an intact part. Each gap, if large enough, turns into a new ALP.
   (c) The inclined encounter usually leads to one of the results given in 2a or 2b. At small angles of collision, however, the new ALP is rotated into the direction of the plane wave.
3. The interaction of an ALP with a train of plane waves can lead to different results depending on the type of encounter and the length of the time interval between the successive plane waves:
   (a) The encounter in opposite directions: (i). If the generation period of the plane waves is smaller than that of a new ALP, then the ALP is gradually annihilated; (ii). If the periods are of the same order of magnitude, the ALP survives but does not multiply; (iii). For longer periods of the plane waves, the ALP and the surrounding target waves drift towards the origin of the plane waves, where they cause wave breakings and multiplications, resulting in complex behavior.
   (b) The encounter in a common direction: (i). If the period between plane waves generation is small relative to that of the ALP's, the state of a plane wave with double-gap persists but is driven away from the plane waves origin. (ii). For periods of the same order of magnitude, the motion of the double-gap structure is in the opposite direction, namely towards the origin of the plane waves, the intact part between gaps meanwhile elongating monotonously. (iii). For longer periods of the plane waves the result is similar to the case 3a(iii).
4. Interactions of ALP's with target waves lead to effects similar to those reached in their interactions with plane waves.

Some immediate indications with regard to heart arrhythmia based on a figure of eight reentry can be drawn from the present work.

A given therapy for arrhythmia is considered effective if it stops the arrhythmia, prevents arrhythmia occurrence/ recurrence or converts non-tolerated to tolerated one. As shown in the paper, normal sinus rhythm is not sufficient to terminate figure of eight arrhythmia. Moreover, the interaction between the source of the reentry and the natural cardiac waves emanating from the sinus node can usually lead to complex (fibrillation like) patterns, both atrial and ventricular fibrillations (AF, VF) depending on the waves encounter location. This happens because the period of the normal sinus pacing is longer than that of the reentry source [1–3]. Implantable cardioverter/defibrillator (ICD) devices, which have been in operation since the first implantable defibrillator in 1980 (Mirowsky), have been very effective in both stopping fibrillation and controlling heart pacing. They proved effective even in terminating VT 70–90% of the time by antiarrhythmia pacing (ATP, no defibrillation). This was achieved by an understanding of the 'regular' spiral reentry syndrome causing tachycardia. Figure of eight type of ectopic source is, however, much less investigated and as a result less understood. The present work indicates the possibility of terminating a figure of eight tachycardia (FET) by rapid pacing. Thus, pacing at three times faster than FET is predicted to either directly terminate the arrhythmia or drive the source to the edge of the heart where it would eventually disappear. Of course, the risk of accelerating the tachycardia by such pacing to a worse type of rhythm or VF should be carefully studied and as with any therapy, the risk/benefit ratio considered prior to instituting such therapy.

Conflict of interest statement

None declared.

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