International Journal of Research and Development in Applied Science and Engineering (IJRDASE)
ISSN: 2454-6844

Modeling Effect of Electromagnetic Interference on Cardiovascular System

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***Abstract*-A mathematical model of the cardiorespiratory synchronization and brain as a sensor to the adverse effect of electromagnetic interference (EMI) on cardiovascular system, in particular the radiated susceptibility, is simulated numerically. The basic unit in the model is a non linear oscillator, Van der Pol Oscillator, which possesses structural stability and robustness. It has the capabilities of reproducing the characteristics of human cardiorespiratory synchronization and after the addition of brain as a sensor, it has the capabilities of explaining the affects of electromagnetic (EM) radiation. The same is confirmed from experimentally obtained data and previous experimental findings. Preliminary analysis suggests that human cardiovascular system is affected by EM radiations even if the radiations are below the threshold specific absorption rate (SAR) limits specified by ANSI.**

Keywords-Nonlinear Oscillators, Modeling, Cardiovascular System, Nonlinear Dynamics, Noise, Synchronization, Electromagnetic Interference, Specific Absorption Rate

1. INTRODUCTION

Proliferation of electrical and electronics devices, intelligence added to these devices, miniaturization, close packaging, etc has resulted in electromagnetic (EM) pollution. Electromagnetic Interference (EMI) is any electric or magnetic emission from a device or system that interferes with the normal operation of another device or system. EMI can have annoying effect (like momentary and random disturbances in radio/TV), disturbing effect (like reset and change of status in computers/ digital equipment) and even catastrophic effect (like burning of electronic components, loss of data, change of threshold settings, improper or unwanted operations and sometimes biological hazards). The EM hazards can have three types of effects on humans: - thermal, non thermal and resonance. EMI can take place in the form of conducted emission (CE), conducted susceptibility (CS), radiated emission (RE) and radiated susceptibility (RS). In this paper, we have analysed the effect of EMI on human's cardiovascular system (CVS). The RS has only been considered being the relevant and important case. The effect of radiation can be divided into frequency (f) bands, namely: radio frequency (RF) (100 KHz <f≤ 300 GHz), intermediate frequency (IF) (300 Hz< f≤ 100 KHz), extremely low frequency (ELF) (0<f≤ 300 Hz) and static (0 Hz). When the radiation is directed on to a person, it will be scattered, reflected or absorbed into the body depending on the field strength, the frequency, dimensions of the body and the electrical properties of the tissues. RF energy is absorbed more efficiently at resonance. In case of an average adult, it is 35 MHz if the person is grounded and 70 MHz if the person is insulated from the ground. Body parts may resonant from 30 MHz to 3000 MHz. The specific absorption rate (SAR) is based on American National Standards Institute (ANSI) standard, which is the rate of energy absorption per mass of tissue measured in W/kg. The study of EMI on CVS has not yet been studied in detail and nothing concrete has been reported till date. In this paper, we have analysed the effect of EMI on human CVS in detail, by modelling the heart as an oscillators, lung as an external force and brain as a sensor of EMI. The robustness and dynamic feature of the model is substantiated by experimental data and previous experimenmental findings. The integrated model of heart-lung interaction via gas exchange, the mechanical interaction and via the central nervous system has been taken into account.

We have chosen Van Der Pol oscillator to model the cardiorespiratory synchronization. The model is capable of reproducing the main statistical and dynamical characteristics of the measured time series, including the form of the spectra, the variability of the heart rate and respiration, as well as of the synchronization phenomena. In the model we have considered the direction of coupling from lungs to heart as the same is obtained from the experimental data of normal adults. The results from experimental data show the synchronization of the order of n: m and also the directionality from lungs to heart, which is the basis of the model which we have considered. The data has been taken from Physionet website (www.physionet.org). Ultimately, the brain is included as a sensor for the adverse effect of EMI on the tissues and hormones. The integrated model of heart-lung interaction via gas exchange, the mechanical interaction and via the central nervous system has been considered. This model allows for the variation of the amplitude and the frequency of the oscillators and the levels of parameters (like oxygen, pressure requirement) caused due to the presence of EMI which has resulted in adverse biological health. Therefore, the model may be used to draw certain conclusions about the adverse biological effect of EMI on human CVS. Finally, it is concluded from the mathematical model that the normal heart, lungs and brain activities can get affected by all types of radiations, even if the radiations are below the threshold SAR limits specified by ANSI.

2. METHOD

2.1 Modeling Coupling among Cardiorespiratory System with the help of Van der Pol equations and Brain as a sensor

The Van der Pol oscillator, in presence of noise, is used to represent the interaction of human cardiovascular and respiratory system [1, 2]. The general nonlinear equation is:

$$\frac{d^2x}{dt^2} - \mu\frac{(1-x^2)dx}{dt} + \omega^2 x = e\sin(vt) + \xi \qquad (1)$$

In equation (1), if μ > 0, the oscillator has a unique stable limit. If μ>>1, the oscillator exhibits relaxation oscillations. The oscillator exhibits weakly nonlinear oscillations and behaves similarly to a simple harmonic oscillator when 0 ≥ μ<<1. The terms $\mu(1-x^2)$ represent a nonlinear damping term. Therefore, positive damping occurs for $|x|> 1$ and negative damping occurs for $|x| < 1$. The $\omega^2 x$ terms act as a linear restoring term. $e\sin(vt)$ is an external forcing term where e is the amplitude of external forcing and v is the frequency of external forcing. The amplitude and frequency of external forcing can be varied to observe synchronization of the Van der Pol oscillator by external forcing.

Now, to be more specific, constants were assigned to some variables of the general Van der Pol oscillator. The parameter μ is equal to 1. ξ has the gaussian delta-correlated noise and has a zero mean and therefore it was assumed that ξ = 0. The ω variable was set equal to the natural frequency, 1. Finally, the frequency of external forcing, v, and the amplitude of external forcing, e, was left as variables. It was noted that it was necessary to choose the frequency ratio, between $\frac{1}{4}$ to $\frac{1}{3}$ in order to demonstrate the desired 3: 1 phase locking typical of the cardiorespiratory system [1]. Therefore, after these substitutions in the equation mentioned above, we got simple Van der Pol oscillator which is used to represent the heart and lungs. The equation now becomes:

$$\frac{d^2x}{dt^2} - \frac{(1-x^2)dx}{dt} + x = e\sin(vt) \qquad (2)$$

To determine the interaction of human cardiorespiratory system we have considered heart as oscillator and lungs as external force. After concluding this, by varying the frequency (v) and amplitude (e) of external force, we look for synchronization. Also, the natural frequency ω can be varied, keeping the frequency ratio, between $\frac{1}{4}$ to $\frac{1}{3}$, to account for the real world situation. To demonstrate the effect of EMI signals, we can assume in equation (1), ξ ≠ 0. EMI signal having certain frequency and amplitude has to be taken into account. If the amplitude of the EMI signal is significant and the frequency is within the range of natural frequency, then there will be slight shifting of natural frequency due to EMI. The slight shifting of natural frequency will not affect the CVS adversely as the rhythms of heart and respirations are not constant. It is noted that if the frequency of the signal is not within the range of natural frequency, then by natural filtering mechanism of the human CVS, the EMI signal will be filtered out.

2.2 The Function for Representation of Brain as Sensor

Consider IF and RF range of frequencies, the dynamics of CVS will not be affected directly by this, till the time the SAR is below threshold as specified by ANSI. However, if we model brain as a sensor to CVS dynamics, then it is bound to affect the CVS dynamics indirectly. The reason for the same is that at certain range of RF frequencies (30 MHz – 3000MHz), specific parts of the body resonate, resulting in higher absorption of the interfering signal. In particular, the brain itself resonates at 400MHz and 700 MHz for adult and child respectively. Thus the signals from the brain (sensor for radiation) to heart will be interfered signals which may result in fluctuation of the blood pressure. Also at these frequencies the tissues will be exhausted due to higher absorption of signals. The tissues will require more oxygen to compensate the exhaustion due to interfering signal. The brain will sense the oxygen level and accordingly the brain sensor will affect the CVS and respiratory dynamics. The fatigue, exhaustion and fluctuation in blood pressure have been verified [5]. Other effects not related to cardiorespiratory system are:- headache and migraines, eye irritation and cataract, loss of appetite, giddiness and dizziness, vomiting sensation, loss of temper and altered concentration and memory loss, anxiety and depression, sleep disruption and altered EEG. If the amplitude of RF is very high it may further result in serious biological effects. The burning of tissues may also result in death. We have brought out that the exposure to RF can affect the CVS dynamics, if we take brain as a sensor. Now consider the ELF frequency, if the frequency is similar to CVS dynamics, then it will affect the oscillator by slightly shifting the natural frequency. We have assume in equation (1), ξ = 0 but EMI signal has certain frequency and amplitude and the same has to be considered in equation (1). If the amplitude of the EMI signal is significant and the frequency is within the range of natural frequency, then there will be shifting of natural frequency due to EMI, however the far frequencies will be filtered out naturally by human CVS. Thus, the ELF will not adversely affect the human CVS as the natural frequency will be shifted slightly and human CVS will work normally. However, if the amplitude of these radiations is very high, they can affect the natural neuroharmones like Melatonin. The Melatonin hormone helps in healthy sleep, maintains body temperature, reduces cholesterol, blood pressure, growth of breast cancer and tendency of blood clot. The direct effect of ELF on Melatonin will result in adverse biological effects as given above. Though brain directly is not affected at this frequency but as a sensor will receive the adverse effect of ELF on Melatonin and will give signal to CVS, resulting in higher pumping of blood by heart, thereby increasing the blood pressure. This phenomenon can be well understood if we consider brain as an O_2 Sensor. The brain monitors changes in partial pressure of O_2 and CO_2 using specialized neural structures, located in the medulla, called central chemoreceptors. The chemoreceptor sense and respond to the requirements of the body as a whole. The function to represent the brain should adjust heart rates and breathing rates according to the levels of partial pressure of

O_2 and CO_2 [2, 3, 4]. Thus, properties of the sine function were applied to the Van der Pol equations of the heart and the lungs to represent the brain. The function for brain when it is represented as O_2 sensor can be represented as: $y = \frac{CO_2}{O_2} = |sin\theta|$ for $0 \le \theta < \frac{\pi}{2}$ and $y = \frac{O_2}{CO_2} = |sin\theta|$ for $\frac{\pi}{2} \le \theta \le \pi$. When y=0, which implies that there the partial pressure of O_2 and CO_2 is zero, the body will want to come to normal condition i.e., y=1. So, the brain will increase the natural frequency and in turn the breathing rate and heart rate increases. Now, adjusting the above function for taking into account the partial pressure of CO_2 and O_2, we have the function as:

$$\left.\begin{array}{l} y = \frac{CO_2}{O_2} = 0.4|sin\theta| \text{ for } 0 \le \theta < \pi/2 \quad (3) \\ y = \frac{O_2}{CO_2} = 2.5|sin\theta| \text{ for } \pi/2 \le \theta \le \pi \end{array}\right\}$$

Now, the frequency can be obtained as ω = $|\dot{y}|=|cos\theta|$. For 3:1 phase locking, the restriction $\frac{1}{4} < \frac{v}{\omega} < \frac{1}{3}$ should be followed. Alternatively, $3v < |cos\theta| < 4v$. Adjusting the above function for taking into account the partial pressure of O_2 and CO_2, we have the function as:

$$\left.\begin{array}{l} 3v < 0.4|cos\theta| < 4v \text{ for } 0 \le \theta < \frac{\pi}{2} \\ (4) \\ 3v < 2.5|cos\theta| < 4v \text{ for } \frac{\pi}{2} \le \theta \le \pi \end{array}\right\}$$

3. RESULTS AND DISCUSSION

3.1 Results obtained from data

3.1.1 Here we have considered the subject data ‘f1y04m’. The duration of the signal is for two hours. The synchronization for subject data ‘f1y04m’ shows that initially there is 9:2 synchronization (flat plateaus) , followed by 5:1 synchronization in the later half (flat plateaus). The synchronization ratio 4:1 is also depicted; however it is a slope which implies that there is absence of synchronization at this ratio (see Fig 1).

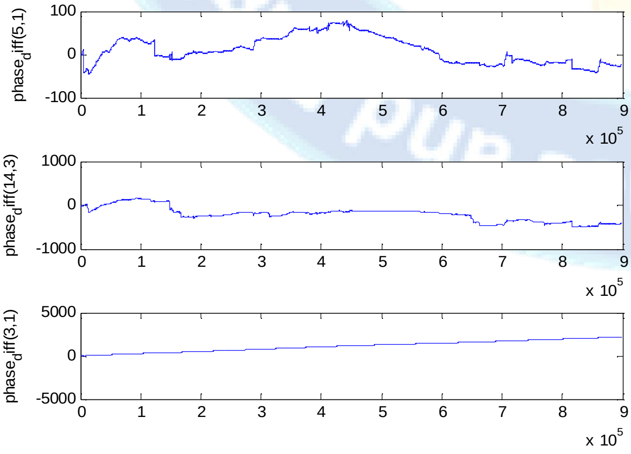

Fig 1: Generalized phase difference for subject ‘f1y04’.

3.1.2 The epoch of synchronization for twenty experimental data were calculated from the phase difference plot. We can deduce that the synchronization/ phase locking is not continuous, it is present in epoch. The locking ratio and time period of epoch varies within a subject and also from subject to subject. The duration of the prominent synchronization period observed is given below in the Table 1:

Table 1: The epoch of synchronization for twenty experimental data

S. No	Code	Sex	Age	Synchronization
1.	f1y01	F	24	11:1(60s),10:1(440s)
2.	f1y02	F	28	10:1(880s)
4.	f1y04	M	44	14:1(976s)
4.	f1y04	M	41	14:4(600s), 5:1(780s)
5.	f1y05	M	24	5:1(80s); 9:2(800s)
6.	f1y06	M	40	14:1(1075s)
7.	f1y07	M	21	6:1(900s), 4:1(200s)
8.	f1y08	F	40	12:1(400s),14:1(400s)
9.	f1y09	F	42	No synchronization
10.	f1y10	F	21	9:1(400s)
11.	f1o01	F	77	12:1(80s),11:1(240s)
12.	f1o02	F	74	11:1(860s)
14.	f1o04	M	74	12:1(946s)
14.	f1o04	M	81	11:1(650s), 12:1(760s)
15.	f1o05	M	76	10:1(80s); 11:1(750s)
16.	f1o06	F	74	14:1(275s)
17.	f1o07	M	68	5:1(900s), 6:1(200s)
18.	f1o08	F	74	12:1(200s),14:1(150s)
19.	f1o09	M	71	10:1(250s); 11:1(750s)
20.	f1o10	F	71	10:1(200s); 11:1(450s)

3.1.3. Directionality index d(h,r) for various subject data are plotted against age of the subject. We can deduce that for an adult individual the directionality from heart to lung is negative (see Fig 2). The negative sign indicates that the interaction between heart and lung is unidirectional. The lungs are driving heart in case of an adult individual. The magnitude of directionality index is varying in a random manner, which suggests that there is no relation of the magnitude of directionality index with age for a specified period of time.

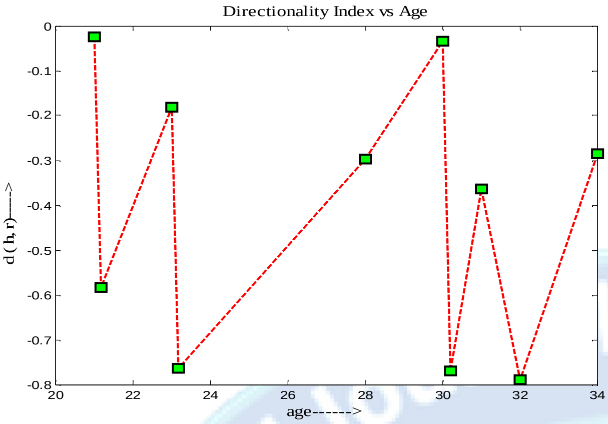

Fig 2: Directionality index d(h,r) versus age

3.2 Results obtained from Van der Pol equations model as cardiorespiratory system

3.2.1 The Van der Pol equation is solved and plotted. It is used as a model to represent the heart in cardiorespiratory system. The x_1 represents $x(t)$ and x_2 represents $\frac{dx(t)}{dt}$ (see Fig 3). The signal $x(t)$ is used for extracting the phase information of the heart.

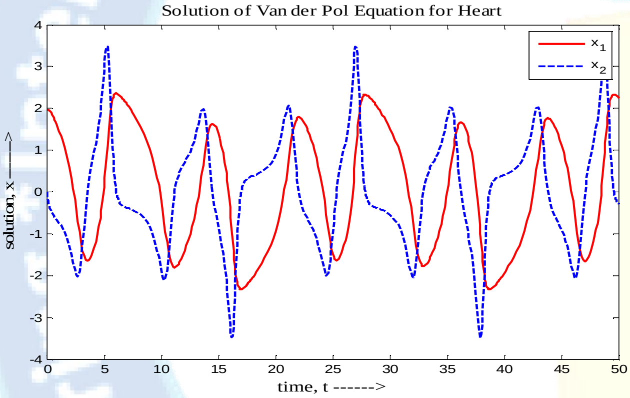

Fig 3: Solution to Van der Pol equation.

3.2.2 The phase plane plot of Van der Pol equation is a closed trajectory (see Fig 4) in phase space, thus it is stable in nature and can be used in modeling heart.

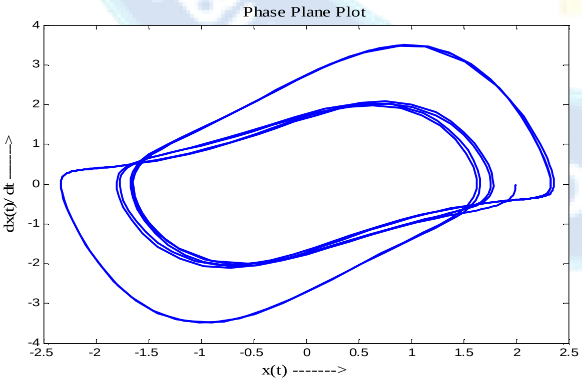

Fig 4: Phase plane plot

3.2.3 Consider the case for v=0.287 and e=0.8, the 3:1 locking. To detect the synchronization we compute the phase difference (3:1)= phase of external force ($3vt$) -phase of Van der Pol. The MATLAB simulation exhibits the phase synchronization (see Fig 5). We can see that the phases of oscillator (dotted line) and external force (continuous line) are in phase. Thus, we can see that there is 3: 1 synchronization between the oscillator and the external force. In other words, we can say that heart and lungs in the model are synchronized in the ratio of 3:1.

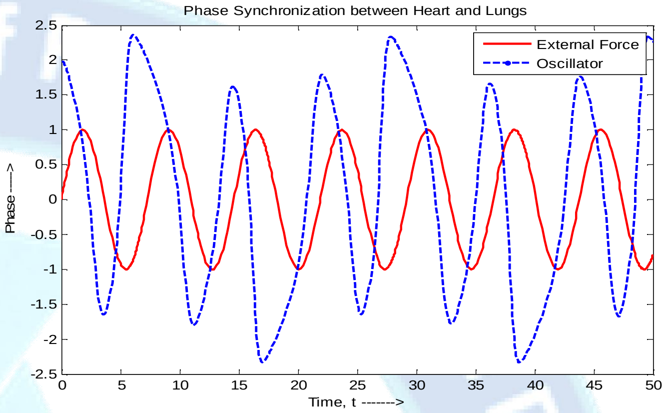

Fig 5: 3:1 Locking between Oscillator and External Force for v =0.287 and e=0.8

3.2.4 The distribution of cyclic relative phase for v =0.287 and e=0.8, has a pronounced maximum that means existence of a preferred value of phase difference (see Fig 6). This is the condition of phase locking. If we decrease the amplitude of the external force below certain threshold, we will get uniform distribution. We can conclude that for phase synchronization the amplitude of the external force has to be above certain threshold.

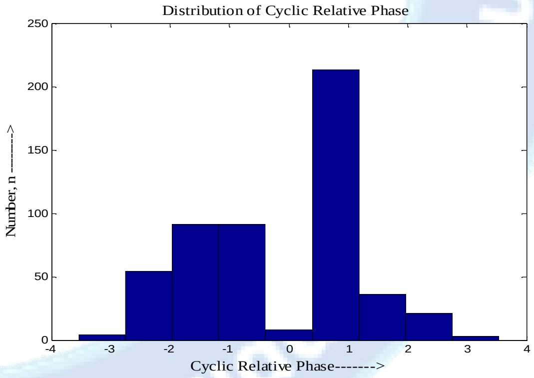

Fig 6: Distribution of cyclic relative phase is unimodal for synchronization

3.2.5 Consider again the case for v =0.3118 and e =0.3 . We compute the phase difference (3:1)= phase of external force ($3vt$) - phase of Van der Pol . The distribution of cyclic relative phase is fairly uniform, implying there is absence of synchronization (see Fig 7). for synchronization the amplitude of the external force has to cross certain threshold.

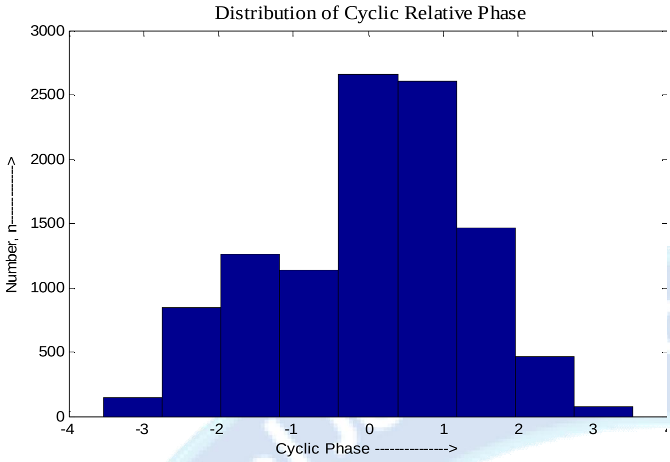

Fig 7: Distribution of cyclic relative phase is uniform for no synchronization

3.2.6 Solution of Van der Pol oscillator for the input frequency of the external forcing (v) = 1, the amplitude of the external forcing (e)= .8 and the natural frequency(ω) = 3 is shown below (see Fig 8). The frequency of oscillator/ heart and the frequency of external forcing/ lungs are increasing, when we increase the natural frequency (compare Fig 8 and Fig 5). The increase in natural frequency is to account for the real world situation.

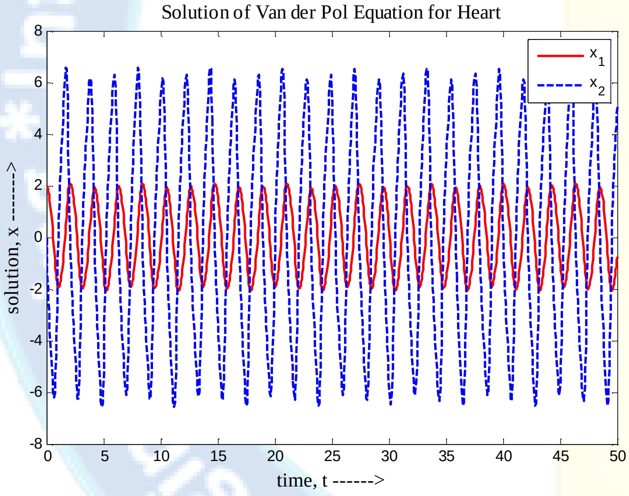

Fig 8: Solution of Van der Pol oscillator for v =1, e =.8 and ω=3

3.2.7. When the amplitude of the external forcing (e) = .8, the frequency of the external forcing (v) = .8 and arterial partial pressure of carbon dioxide (in mm Hg) =35 and arterial partial pressure of oxygen (in mm Hg) =105, there is deficiency of carbondioxide level or increase of oxygen level by 5 mm of Hg. The brain reacted by increasing the heart rate and the breathing rate (see Fig 9) which is directly proportional to the deficiency of carbondioxide / increase of oxygen level in the body. We can also simulate that the increase in frequency of the heart rate is less if we consider the amplitude of the external forcing (e) = .8, the frequency of the external forcing (v) = .8 and arterial partial pressure of carbondioxide (in mm Hg) = 0 and arterial partial pressure of oxygen (in mm Hg) =140

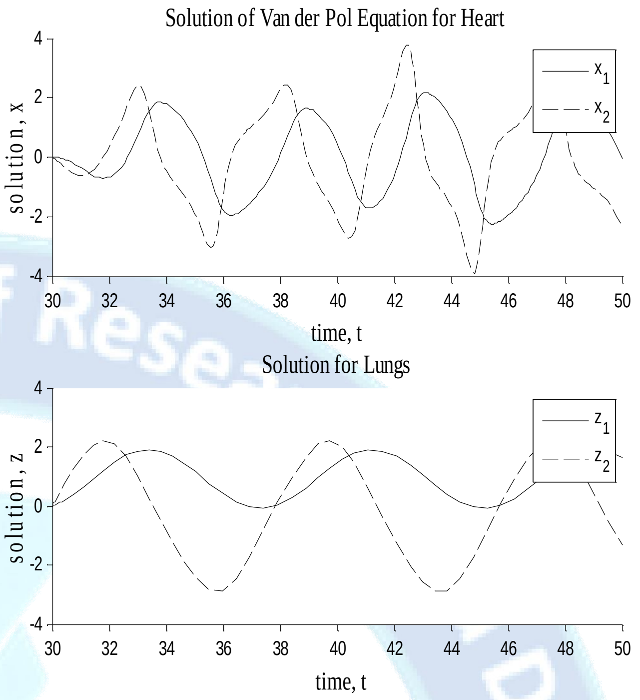

Fig 9: Solution of Van der Pol oscillator for v =.8, e =.8, partial pressure of CO_2=35 and partial pressure of O_2=105

3.2.8. When the amplitude of the external forcing (e) = .8, the frequency of the external forcing (v) = .8 and arterial partial pressure of carbon dioxide (in mm Hg) =40 and arterial partial pressure of oxygen (in mm Hg) =100, the brain did not sense a need for a change in the heart rate or the breathing rate as the levels of carbondioxide and oxygen are normal (see Fig 10).

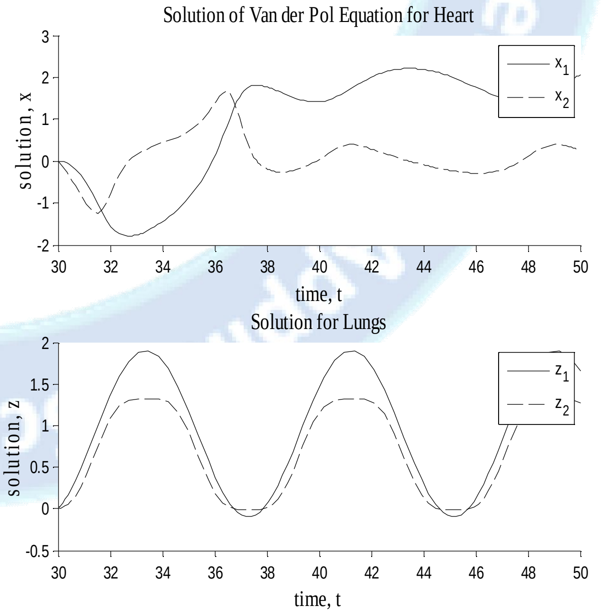

Fig 10: Solution of Van der Pol oscillator for v=.8, e=.8, partial pressure of CO_2=40 and partial pressure of O_2=100

3.2.9. Consider IF and RF range of frequencies, at certain range of RF frequencies (30 MHz – 3000MHz), specific parts of the body resonate, resulting in higher absorption of the interfering signal thereby resulting in the exhaustion of the tissues. Thus the signals from the brain (sensor for radiation) to heart will be interfered signals which may result in fluctuation of the blood pressure. Also at these frequencies the tissues will be exhausted due to higher absorption of signals. The tissues will require more oxygen to compensate the exhaustion due to interfering signal. The brain will sense the oxygen level and accordingly the brain sensor will affect the CVS and respiratory dynamics. The fatigue, exhaustion and fluctuation in blood pressure have been verified. Consider the amplitude of the external forcing (e)= .8, the frequency of the external forcing (v)= .8 and arterial partial pressure of carbon dioxide (in mm Hg)=140 and arterial partial pressure of oxygen (in mm Hg) =0, there is increase of carbondioxide level or decrease of oxygen level by 60 mm of Hg. The brain reacted by increasing the heart rate and the breathing rate (see Fig 11) which is directly proportional to increase of carbondioxide level/ deficiency of oxygen in the body. We can simulate that the increase in frequency of the heart rate is more if we consider the arterial partial pressure of carbon dioxide (in mm Hg) =70 and arterial partial pressure of oxygen (in mm Hg) =70.

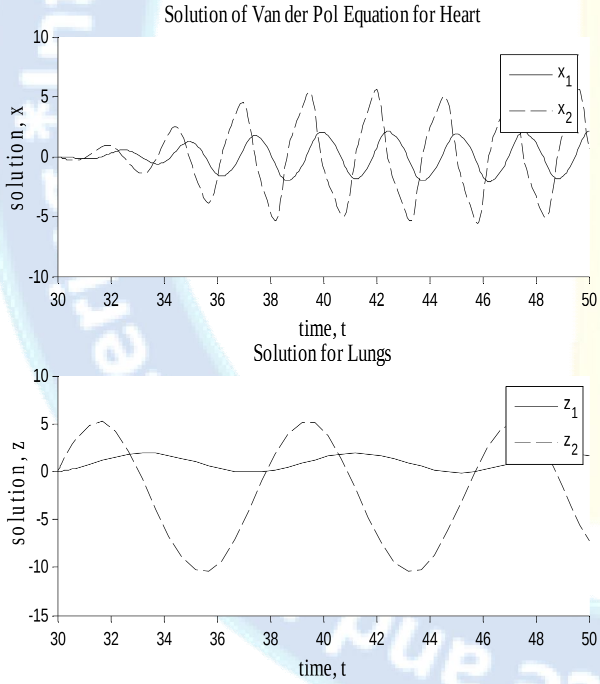

Fig 11: Solution of Van der Pol oscillator for v=.8, e=.8, partial pressure of CO_2=140 and partial pressure of O_2=0

3.3 General discussions and Findings:

1. The Van der Pol equations modelled as oscillator and external force resembles the experimentally obtained data when the direction of coupling is from lungs to heart.
2. When the frequency ratio of external force and oscillator are in the ratio of 3: 1 to 4: 1 and there is phase locking, however, the amplitude of the external force has to be greater than certain threshold.
3. If the frequency ratio of lungs and heart are in the ratio of 3: 1 to 4: 1 but the amplitude of the external force is less than threshold, there is no phase locking.
4. The model can work under real world situation, where the natural frequency is greater than 1. In that case, the increase in natural frequency results in the increase in the frequency of the oscillator and the external force. In other words, the increase in natural frequency results in increase of heart rate and the breathing rate.
5. The Van der Pol equations used for representing heart and lungs can further be modified by introducing brain as an sensor.
6. The normal levels of oxygen and carbondioxide in the body are 40mm and 100mm of Hg. If the level of oxygen/ carbondioxide changes in the body, the brain senses it and accordingly increases the heart rate and breathing rate. If the levels are normal, then there is no change in the heart rate and breathing rate.
7. At certain range of RF frequencies (30 MHz – 3000MHz), specific parts of the body resonate thereby increasing the carbondioxide content, resulting in higher absorption of the interfering signal. Thus the signals from the brain (sensor for radiation) to heart will be interfered signals which may result in fluctuation of the blood pressure .
8. The ELF below threshold will not adversely affect the human CVS as the natural frequency will be shifted slightly and human CVS will work normally. However, if the ELF threshold is more, it will affect the harmones and indirectly brain as a sensor will affect the cardiorespiratory system.
9. With the help of this model we can investigate the variation of the amplitude and the frequency of the oscillators and the affect of EM radiations on cardiorespiratory system.
10. We can also understand how the body behaves when the cardiorespiratory system is subjected to ELF, IF and RF. Also, we can understand the affect of deficiency of oxygen level/ increase of carbondioxide level in the body or vice versa and the affect of ELF on hormones which thereby indirectly effect the cardiorespiratory system.

4. Conclusion

We have found from the experimental data that the respiratory signal and ECG signal for different persons are quite different. Both the signals show high variability and individual differences. However in almost all the cases there is interaction between the cardiorespiratory system and it is unidirectional (from lungs to heart). We found that there were epochs of synchronization present in nearly all the experimental data considered. Thus, cardiorespiratory system can be modelled as a non linear, Van der Pol, oscillator. From the phase plane plot we conclude that the Van der Pol oscillator is stable and can be used to represent the heart. The interaction of Van der Pol oscillator and external force exhibited synchronization which resembles the cardiorespiratory interaction in human. We can further conclude that the amplitude of the external force has to cross certain threshold so that there is synchronization between Van der Pol oscillator and external force, which implies that the amplitude of respiration has to cross certain threshold so that there is phase synchronization between heart and lungs. We have also incorporated brain as a sensor which increases heart rate and respiration rate according to the level of O_2 in the blood. The level of O_2 is affected by RF exposure. After analysing the Van der Pol oscillator as heart, external force as lung and brain as a sensor of EM radiation, we conclude that the cardiorespiratory system is affected by ELF, IF and RF.

5. Scope for future work

In future, the accurate heart signals and respiratory signals at various threshold of ELF, IF and RF can be taken . This will explain the erratic behavior of EM radiations on heart and lung functioning. Thus important conclusion can obtained regarding the fluctuating blood pressure, breathing problems and fatigue in EM environment. The EM radiations absorbtion limits can further be aligned based on this model. Similar, modeling of other human system and the effect of ELF, IF and RF on these system can be done. Finally the individual systems can be integrated and the affect of the radiations can be generalized for humans.

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