Modeling effects of the electromagnetic radiations on the cardiovascular system

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***Abstract*— The Cardiovascular system (CVS) consists of the heart and blood vessels. The activities of heart and lung are responsible for pumping and return path of the blood through a closed circuit of elastic vessels. Time-frequency analysis of blood flow, ECG and respiratory signals revealed the existence of five almost periodic frequency components having average frequencies of 1.0, 0.2, 0.1, 0.03 and 0.01Hz due to heartbeat, respiration, myogenic activity of smooth muscles, neurogenic and endothelial activity respectively. We have demonstrated the effects of the electromagnetic radiations (EMRs) on the CVS by modeling the CVS as nonlinear coupled oscillators having basic unit as Poincare oscillators and concluded that the blood flow is influenced by EMRs, thereby resulting in adverse effect on CVS. The safety standards for thermal, non-thermal and resonance effects of EMRs can be derived based on this model.**

Keywords*— electromagnetic fields; nonlinear oscillators; modeling; cardiovascular system; noise; coupling; thermal effects; non-thermal effects; resonance effects; electromagnetic radiations; directionality; synchronization

I. INTRODUCTION

Earlier Electromagnetic Pollution affected only certain “exposed” persons who were vulnerable (Vocation and Demographics). Today we live in a world that is increasingly “wired” and the entire population is affected by electromagnetic pollution. The growth of cell phones has been extraordinary, mobile phone towers are everywhere, wi-fi technologies are now in most homes. Domestic appliances like Microwave Oven, Induction Cookers, Computers, TV, USB Powered Devices, etc are generating EMRs. Our environment is saturated by wireless technologies across the frequency spectrum and various types of emissions. We cannot help being affected by EMRs from these man-made Electromagnetic Fields (EMFs). EMRs have harmful effects on human beings. Even low level EMRs can cause biological damage. In this paper, we have analysed the EMRs Effects on human CVS in detail, by modeling the CVS dynamics as a system of five coupled nonlinear oscillators having basic unit as Poincare oscillator [6-8]. These oscillators represent the heart, respiration, myogenic activity, neurogenic activity and the endothelial related metabolic activity. We have presented the results of numerical simulations of the proposed model by considering linear coupling in presence of noise as it closely resembles the actual spectrum of CVS dynamics [6-7].

The effects of EMRs on human beings largely depend on frequency, duration and power of the EMRs [1-2]. The effects of radiations can be broadly discussed under Thermal, Non-Thermal and Resonance Effects. The brief features and status of the safety standards of various effects of EMRs are tabulated below in Table I.

TABLE I. Effects of EMRs

Effects of EMRs	Features/ Reasons	Safety Standards
Thermal	• High power • Short/medium/long duration • Permanent damage	• Safety Standards exist (Example: SAR – Specific Absorption Rate) [2-3].
Non-Thermal	• Low power • Long duration • Damage may be reversible	• Guidelines stated by International Commission on Non –Ionizing Radiation Protection (ICNIRP) guidelines [4].
Resonance	• Resonance Principle • Frequency Dependent • Cyclonic Resonance (lower frequencies) • Oscillation Resonance (higher frequencies) • Size of target organ is of the order of Wavelength of the EMRs. • Body parts may resonant from 30 MHz to 3000 MHz [5].	• Safety Standards not yet formulated.

Thermal effects occur only for radiation of microwave frequencies and above. Low frequency influence on an organism does not lead to a marked tissues heating since thermal energy, which is absorbed by the tissues at this, is less than metabolic heat production. EMRs, especially Microwaves, cause heating which can burn / damage / alter chemical composition of the Target Victim Entity. Clinical manifestation of microwave influence on a human organism with different radiation intensity (B.A. Minin's modification with data addition, 1974) is tabulated below in Table II.

TABLE II. Microwave influence on a human organism

Microwave intensity, mW/sm	Changes observed
100	Blood pressure increase followed by its decrease, in case of chronic exposure – stable hypotension. Double-sided cataract.
40	Warmth sensation. Vessels dilation. During exposure blood pressure increases by 20-30 mm of mercury.
10	After 15-minute exposure asthenisation and change in brain bioelectric activity are observed
8	General radiation period being 150 hours, vague shifts with regard to blood and changes in coagulability are observed
6	Electrocardiographic changes and changes in receptor system
4-5	Changes in blood pressure in case of multiple exposure, Short-term leukopenia, erythropenia
3-4	Vagotonic response with bradycardia symptoms, heart conductivity slowing-down
2-3	Marked blood pressure lowering, more rapid pulse, heart blood volume fluctuations
1	Blood pressure lowering, rapid pulse trend, insignificant heart blood volume fluctuations. If exposure exists every day within 3.5 months intraocular pressure reduces.
0.4	Under pulse electromagnetic radiation exposure acoustic effect is observed
0.3	Some changes in the nervous system under chronic exposure within 5-10 years
0.1	Electrocardiographic (ECG) changes
Less than 0.05	Blood pressure lowering trend under chronic exposure

Non-Thermal effects- With regard to low frequency (< 10 Hz) electromagnetic fields, a human body possesses a conductor's properties. Under an external field influence, conduction current appears in tissues. The length of low frequency electromagnetic waves significantly exceeds the dimensions of a human body; as a result the whole organism undergoes such wave's exposure. However, the effect on different tissues is not the same since both their electric properties and sensitivity to conduction current are different. It is the nervous system that is quite sensitive to it. The induced conduction current passes mostly through extracellular fluids, since their resistance is much less than that of the cell membranes. Low frequency electromagnetic field's influence on an organism does not lead to a marked tissues heating since thermal energy, which is absorbed by the tissues at this, is less than metabolic heat production. The non thermal effects of EMRs are:

- DNA Damage
- Gene Mutation
- Chromosome Aberrations
- Comet Assay
- Electrophoresis
- Genotoxic Effects (Brain Damage)
- Neurological Effects (Behavioral Problems)
- Hormonal Imbalance

Resonance Effects- It is based on Resonance Principle and is frequency dependent. It is broadly classified as Cyclonic Resonance and Oscillation Resonance. As shown in Fig. 1, the Cyclonic Resonance is due to lower frequencies and it builds up like cyclone whereas Oscillation Resonance is due to higher frequencies and harmonics. In resonance effect the size of target organ is of the order of the wavelength of EMR. The non thermal effects of EMRs can be:

- Blood pressure increase/ decrease/ fluctuation
- Changes in blood pressure
- Asthenisation, fatigue, irritability,weakness
- heart blood volume fluctuations
- Electrocardiographic (ECG) changes
- Sexual Dysfunction due to Cyclonic Resonance in Nervous System
- Impotence due to Oscillation Resonance in Scrotum, Uterus and Cells (Disturbs Sperm Formation and Ovulation Cycle)
- Damage to Embryo in Pregnant Women

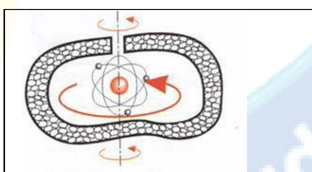	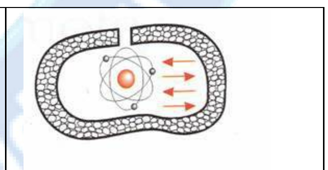
Cyclonic Resonance of Human Cells occurs in the 30-50 Hz range.	Oscillation Resonance of Human Cells occurs at microwave frequencies

Fig.1 Cyclonic Resonance and Oscillation Resonance

We have modeled the CVS and shown that the how the blood flow is influenced under the thermal, non-thermal and resonance effects of EMRs. Therefore, the model may be used to draw certain conclusions about how the human body responds to thermal, non-thermal and resonance effects of

EMRs [. The directionality is considered from lungs to heart as the same is obtained from the results of experimental data for all healthy adults. The data has been taken from Physionet website (www.physionet.org). The robustness and dynamic feature of the model is substantiated by experimental data and previous experimental findings [16-17]. Finally, we have summarized the results and drawn conclusions.

II. Method

A. Modelling Coupling among the Oscillators of CVS with the Basic Unit as the Poincare Oscillator

From the experimental observations of the CVS, we can conclude that there are five time scales involved having average frequencies of 1, 0.2, 0.1, 0.03 and 0.01Hz due to heartbeat, respiration, myogenic, neurogenic and endothelial related metabolic activity respectively. These subsystems behave as autonomous oscillators. Analysis of cardio-respiratory synchrograms shows synchronization among the cardiorespiratory oscillators in the ratio of n: m. The blood flow of healthy individual always has one of the Lypunov exponents approximately equal to zero, suggesting that the CVS signal is deterministic and can be represented by differential equations. Thus each oscillation observed in the CVS signals can be modeled as Poincare oscillator and the interactions between the subsystems as couplings between the oscillators. It can be represented by:

$$\dot{x_i} = - x_i q_i - y_i \omega_i + g_{x_i}(\mathbf{x}); \; \dot{y_i} = - y_i q_i + x_i \omega_i + g_{y_i}(\mathbf{y}) \text{ and } q_i = \propto_i \left(\sqrt{{x_i}^2 + {y_i}^2} - a_i\right) \qquad (1)$$

where, x (blood flow) and **y** (velocity of flow) are vectors of oscillator state variables. $\propto_i$, a_i and ω_i are constants and $g_{y_i}(\mathbf{y})$ and $g_{x_i}(\mathbf{x})$ are linear coupling vectors; i =1, 2,3,4 and 5 corresponds to heart, respiration, myogenic, neurogenic and metabolic oscillators respectively.

B. Simplified version of CVS

The simplified version can be represented by:

$$\dot{x_1} = - x_1 q_1 - y_1 \omega_1 + \eta_2 x_2 - \eta_3 x_3 - \eta_4 x_4 + \eta_5 x_5 \qquad (2)$$
$$\dot{y_1} = - y_1 q_1 + x_1 \omega_1 + \eta_2 y_2 - \eta_3 y_3 - \eta_4 y_4 + \eta_5 y_5 \qquad (3)$$

$$\dot{x_2} = - x_2 q_2 - y_2 \omega_2 + \theta_4 x_4 - \theta_5 x_5 \qquad (4)$$
$$\dot{y_2} = - y_2 q_2 + x_2 \omega_2 + \theta_4 y_4 + \theta_5 y_5 \qquad (5)$$

$$\dot{x_3} = - x_3 q_3 - y_3 \omega_3 + \gamma_4 x_4 - \gamma_5 x_5 \qquad (6)$$
$$\dot{y_3} = - y_3 q_3 + x_3 \omega_3 + \gamma_4 y_4 - \gamma_5 y_5 \qquad (7)$$

$$\dot{x_4} = - x_4 q_4 - y_4 \omega_4 - \rho_2 x_2 + \rho_3 x_3 - \rho_5 x_5 \qquad (8)$$
$$\dot{y_4} = - y_4 q_4 + x_4 \omega_4 - \rho_2 y_2 + \rho_3 y_3 - \rho_5 y_5 \qquad (9)$$

$$\dot{x_5} = - x_5 q_5 - y_5 \omega_5 + \sigma_2 x_2 - \sigma_3 x_3 - \sigma_4 x_4 \qquad (10)$$
$$\dot{y_5} = - y_5 q_5 + x_5 \omega_5 + \sigma_2 y_2 - \sigma_3 y_3 - \sigma_4 y_4 \qquad (11)$$

where η_i , θ_i , γ_i , ρ_i and σ_i are coupling terms.

For simplification purpose and to reproduce the time series and power spectra to be similar to experimental data, the parameters were set as given below. These parameters were further altered to consider the resonance effect of EMRs.

$\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = 1$
$a_1 = a_5 = 0.5$; $a_2 = a_3 = a_4 = 1$
$\eta_2 = -\eta_3 = -\eta_4 = \eta_5 = 0.5$
$\theta_4 = \theta_5 = 0.1$
$\gamma_4 = \gamma_5 = 0.1$
$\rho_2 = \rho_3 = \rho_5 = 0.1$
$\sigma_2 = \sigma_3 = \sigma_4 = 0.1$
$\eta_6 = \eta_7 = \theta_6 = \theta_7 = \gamma_6 = \rho_6 = \sigma_6 = 0$
f_1, f_2, f_3, f_4 and f_5 varied but close to the average frequencies of the subsystem

A fluctuation term, ξ (t) such that $< \xi(t)> = 0$ as $< \xi(t)\xi(0)> = D\delta(t)$, was added to the cardiac oscillations while considering noise. Thus heart can be represented by:

$$\dot{x_1} = - x_1 q_1 - y_1 \omega_1 + g_{x_1}(\mathbf{x}) + \xi(t) \qquad (12)$$

C. Thermal effects of EMR on CVS

In case of thermal effect, asthenisation (feeling of weakness without actual loss of strength), fluctuating blood pressure, irregularity of heart beats and change in ECG is observed. We have simulated the above results by altering the value of coupling constants. This model allows for the variation of the amplitude, the frequency and the value of coupling constants of the oscillators thereby above effect can be simulated.

D. Non -Thermal effects of EMR on CVS

In case of non-thermal effect, there will not be marked tissues heating since thermal energy, which is absorbed by the tissues, is less than metabolic heat production. This will directly not affect the CVS dynamics. However, the non-thermal effects as brought out in Table II above will indirectly influence the CVS dynamics therefore, we have not simulated the non-thermal effects.

E. Resonance effects of EMR on CVS

In case of resonance effect, different target organs and body as a whole will resonate, thereby the absorption of radiations will increase [5]. This will result into more activity of body cells, tissues and organs, thus more exhaustion of body parts and increase in the requirement of oxygenated blood. In normal scenario, the cardiac oscillator will receive action potential stimulus from auto nervous system (ANS) which will affect heart rate, volume and resistance of blood vessels [9-13]. However, the action potential from ANS may also get influenced due to resonance of brain, as it is controlled by hypothalamus part of the brain. This will result in fluctuating blood pressure, irregularity of heart beats and thus affects the normal functioning of CVS system. We have simulated the above results by altering the value of coupling constants. This model allows for the variation of the amplitude, the frequency and the value of coupling constants of the oscillators.

III. Results and Discussions

A. *Results Obtained from Data*

- Quantification of interaction between heart and lung: The synchronization index from phases and directionality index for various subject data are calculated (see Table III). There is phase synchronization between lung and heart. It is not perfect but epoch of synchronization is present. The directionality index is negative suggesting that there is directionality from lung to heart.

TABLE III. Quantification of interaction between heart and lung

Data	Synchronization index from phases	Directionality index
f1y01m	0.082472	-0.18188
f1y02m	0.11714	-0.29774
f1y03m	0.10448	-0.28581
f1y04m	0.074225	-0.46454
f1y05m	0.074405	-0.76421
f1y06m	0.18454	-0.044598
f1y07m	0.15444	-0.024598
f1y08m	0.082076	-0.76929
f1y09m	0.070076	-0.78979
f1y10m	0.170026	-0.58248

B. *Modeling Coupling Among the Oscillators of CVS*

- Results of modeling the linear couplings in the absence of noise, presence of noise and parametric coupling are shown below (see Fig 2). The time series of Poincare oscillator modeled as heart and respiration resembles the experimentally obtained data.

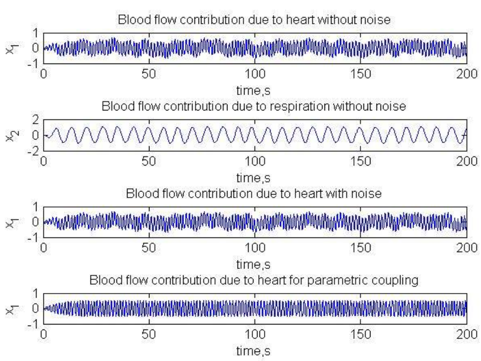

Fig. 2. First, third and fourth from top, shows cardiac oscillators for linear coupling without noise, with noise and parametric coupling respectively. Second from top, shows the respiratory oscillator

- It is seen that the width of the peaks of the power spectrum obtained by modeling differs substantially with experimentally obtained data (Fig 3). This suggests that the linear coupling dominates the parametric coupling. Also, power spectra of linear coupling in presence of noise resemble the experimentally obtained data.

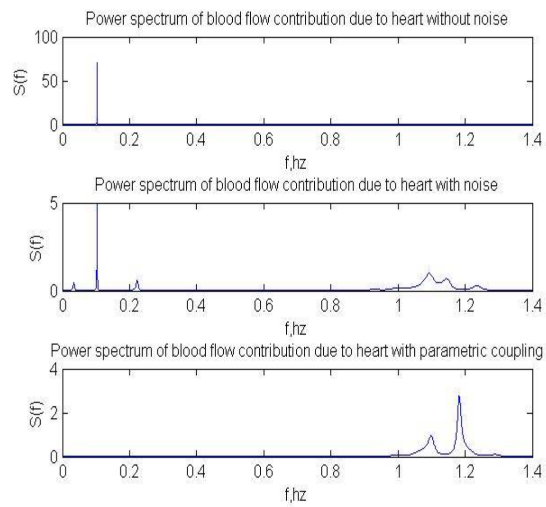

Fig 3: Power spectrum of the time series for the flow generated by cardiac oscillator, x_1 for linear coupling without noise, with noise and parametric coupling respectively

- Thermal effect increases endothelial related metabolic activity, which in turn will alter the coupling term due to endothelial related metabolic activity. The altering of coupling term will affect the respiratory and cardiac oscillator (Fig 5). Thus the fluctuating blood pressure and irregular heartbeats are justified (Fig 4).

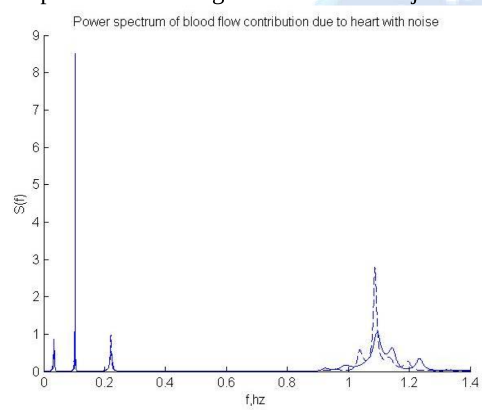

Fig. 4.

Fig 4: Dotted line shows that if we increase the coupling term due to endothelial related metabolic activity, there are prominent rise in the power spectrums of respiratory and cardiac oscillators.

- Resonance effect increases endothelial related metabolic activity, which in turn will alter the coupling term due to endothelial related metabolic activity. The altering of coupling term will affect the cardiac oscillator (Fig. 5) and respiratory oscillator (Fig. 6). Thus the fluctuating blood pressure, irregular heart beats are justified.

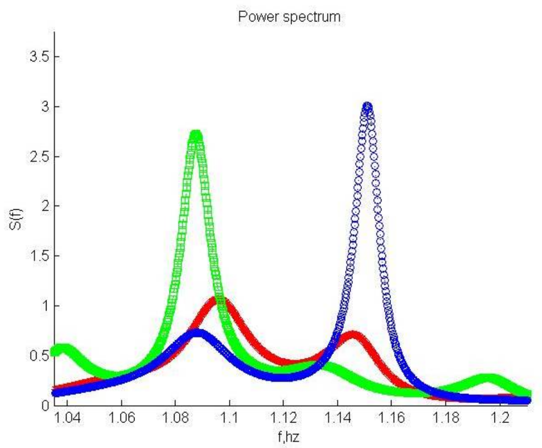

Fig. 5. Varying the coupling term due to endothelial related metabolic activity, results in prominent variations in the power spectrums of blood flow generated by cardiac oscillator

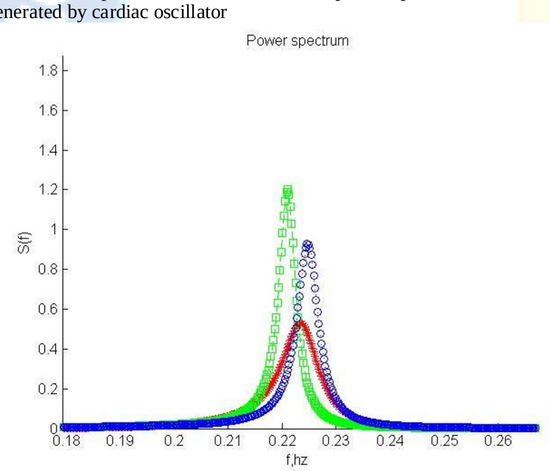

Fig. 6. Varying the coupling term due to endothelial related metabolic activity, result in promonent variations in the power spectrums of blood flow generated by respiratory oscillator

IV. Conclusion

The time series of linearly coupled Poincare oscillators in presence of noise, modeled for CVS dynamics, resemble the experimentally obtained data. Due to EMR effects, the blood flow of an individual will vary as the output of cardiac and respiratory oscillators will vary, thereby resulting in fluctuating blood pressure, irregularity of heart beats and thus affects the normal functioning of CVS system.

V. Scope for Future Work

In future, the accurate heart signals and respiratory signals at various thresholds of ELF and RF can be modeled and extrapolated to analyse the EMRs effect. The alteration of coupling constant due to EMR effect can be obtained experimentally and the absorption limits of EMRs can further be worked out and aligned based on this model.. This will explain the erratic behavior of EMRs on CVS functioning. Thus important conclusion can be obtained regarding the fluctuating blood pressure, breathing problems and fatigue in EM environment. Similar, modeling of other human systems including brain can be done and the EMRs effect can be modeled.

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