Quantum Biological Thermodynamics with Finite Speed of the Cardio-Pulmonary System

II- Computation of power and the entropy source of the cardio pulmonary system

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The paper presents the results of the recent studies and research conducted within the Quantum Biological Thermodynamics with Finite Speed of the Cardio-Pulmonary System performance. Thus, based on the new PV/Px diagram developed for the Cardio-Respiratory System, an original Scheme for calculating the Mechanical Work and Power of the Heart/Lungs has been developed. The new Calculation Scheme allows to study the variation of the Heart and Lungs parameters for each person, in Quantum States and in Processes with and without Quantum Jump. Based on the values calculated in each Stationary State, for the cases studied, the diagrams of the Mechanical Work, of the total Power and the Entropy Source for the Cardio-Pulmonary System, as functions of the Frequencies of the Heart (F_H), and the Lungs (F_L), the maximum systolic pressure and body mass of the person were thus constructed. The study and interpretation of these diagrams - which are novel elements - provides information on interactions within the Cardio-Pulmonary System or between it and the entire body, particularly useful in bioengineering for optimized and personalized design of artificial organs.

Keywords: Quantum Biological Thermodynamics with Finite Speed, Cardio-Pulmonary System, Processes with and without a Quantum Jump, Stationary States, artificial Organs, Mechanical Work and Power computation, Entropy Source

Experimental part

Scheme for calculation of Mechanical Work, Power and Source of Entropy of the Cardio-Pulmonary System

The Power of the Heart [5] can be expressed using the new chart PV/Px from QBTFSCPS by taking into account the losses caused by throttling in the valves of the Heart.

On average, the dimensions of the human Heart are: h (height) = 0.12 m; l (width) = 0.08 m, according to the literature [16-25]. To simplify the calculations, the Heart was considered as having the shape of a circular truncated cone with the smaller base downward (fig. 1). The bases diameters of the circular truncated cone (large and small) are D = 2 · R and d = 2 · r and its height is h. In order to keep the human Heart dimensional proportionality as rigorous as possible, one considers that D = 4 · R and d = 2 · r. Therefore, the relationship between the radii of the two bases is R = 4 · r. During Cardiopulmonary System operation, the Cardiac Output (flow rate), CO [m3/min.], is considered to be 5-6 m3/min at rest...
where \( m_{body} \) is the mass of the body [kg].

The Cardiac Output, \( CO \), is determined based on the relation:

\[
CO = \frac{V_{TB}}{t} \quad \text{[m}^3\text{/min]}
\]

where \( t = 1 \text{ min} \) is the time frame in which the Heart ejects the entire Heart rate into the body [16, 19, 20].

Therefore, at a Stroke (oscillation) of the Heart, the Cardiac Output pumped (volume/stroke), \( CO_0 \text{[m}^3\text{/stroke]} \), results when also considering eq. (2) as:

\[
CO_0 = CO \cdot \frac{N_s}{N_s - t} = \frac{k_B \cdot m_{body}}{N_s - t \cdot \rho_B}
\]

where \( N_s \) is the number of Strokes per minute of the Heart [strokes/min], so that \( N_s = F_H \), with \( F_H \), Frequency of the Heart [osc/min].

We consider \( V_{ds} \) - the Volume of the Heart during the diastole and \( V_{ss} \) - the Volume of the Heart immediately after the systole. Thus, during a complete pulse of the Heart we have:

\[
V_{ds} - V_{ss} = CO_0 \quad \text{[m}^3\text{/stroke]}
\]

Finally, it results:

\[
V_{ds} = \frac{7 \cdot \pi \cdot h_{ds} \cdot R_{ds}^2}{16}
\]

Similarly, one gets:

\[
V_{ss} = \frac{7 \cdot \pi \cdot h_{ss} \cdot R_{ss}^2}{16}
\]

where:
- \( R_{ds} = l_s / 2 \) is the large radius of the truncated cone during the diastole [m];
- \( h_s \) - Heart height during the diastole [m];
- \( R_{ss} = l_s / 2 \) the large radius of the base of the truncated cone immediately after the systole [m];
- \( h_{ss} \) - the Heart height immediately after the systole [m].

To simplify the calculations, we considered \( h_{ss} = h_s = h \) with respect to the Volume of blood pumped from the Heart during an oscillation and together with eqs. (3) and (4) it results:

\[
V_{ds} - V_{ss} = \frac{7 \cdot \pi \cdot h_{ds} \cdot R_{ds}^2}{16} = \frac{V_{TB}}{F_H \cdot t}
\]

By combining eq. (8) with (1), one gets:

\[
R_{ds}^2 - R_{ss}^2 = \frac{16 \cdot k_B \cdot m_{body}}{7 \cdot \pi \cdot h_{ds} \cdot F_H \cdot \rho_B}
\]

and

\[
R_{ss} = \sqrt{R_{ds}^2 - \frac{16 \cdot k_B \cdot m_{body}}{7 \cdot \pi \cdot h_{ds} \cdot F_H \cdot \rho_B}} \text{[m]}
\]

The expansion of the Heart (the dimensional variation on the three axes xyz considered equal), \( z_H \text{[m]} \), is:

\[
z_H = 3 \left( R_{ds} - R_{ss} \right) = 3 \left( R_{ds} - \frac{V_{TB}}{7 \cdot \pi \cdot h_{ds} \cdot F_H \cdot \rho_B} \right)
\]

By taking into account eqs. (3) and (8), the change of the Heart Volume at a Pulsation (Stroke) can be also expressed as:

\[
CO_o = \Delta V_{H,stroke} = V_{ds} - V_{ss}
\]

The Mechanical Work of the Heart on one oscillation is determined as follows:

\[
W_{H,H} = \Delta P_{H,H} \cdot k_B \cdot m_{body} \quad \text{[J]}
\]

where \( \Delta P_{H,H} \) represents the total pressure variation in the Heart compartments during a complete pulse and corresponds to:

\[
\Delta P_{H,H} = \Delta P_{H,left} + \Delta P_{H,right} \quad \text{[Nm}^2\text{]}
\]

with:

\[
\Delta P_{H,left} = \left( \frac{P_{H,s,max,left} - P_{H,LA}}{760} \right) \cdot 10^{-5} + 3 \cdot \Delta P_{H,thr}
\]

\[
\Delta P_{H,right} = \left( \frac{P_{H,s,max,right} - P_{H,RA}}{760} \right) \cdot 10^{-5} + 3 \cdot \Delta P_{H,thr}
\]

where:
- \( P_{H,s,max,left} \) - the maximum systolic Pressure measured with a blood pressure monitor on the left side of the Heart (mmHg);
- \( P_{H,LA} \) - the Pressure (7±12 mmHg) at the circulation of the oxygenated blood through the four pulmonary veins in the left auricle;
- \( P_{H,s,max,right} \) - maximal systolic Pressure (15±25 mmHg) at the circulation of venous blood through the pulmonary artery to the right ventricle into the two Lungs - through the small and larger left pulmonary arteries [mmHg];
- \( P_{H,RA} \) - the blood Pressure to pass from the cave veins into the right auricle (0±9 mmHg) [16].

Pressure losses by throttling through the valves, \( \Delta P_{H,thr} \) [Pa], can be calculated by taking into account the laws of conservation the mass of fluid (Continuity Equation) and preserving the energy of the fluid (Bernoulli Equation), which circulates through a Pressure reduction section [26]:

\[
\Delta P_{H,thr} = \frac{w_B^2 \cdot \rho_B}{2} \left( \frac{S_{H,thr}}{S_v} \right)^2 - 1
\]

in which \( w_B \text{[m/s]} \) - the mean speed of the blood during its flow through the Heart compartments, \( S_{H,thr} \) - the circular crown surface of the medial cross section of the truncated cone to the Volume variation of the Heart between the systole and diastole, and \( S_v \) - the mean surface of a valve of the Heart with diameter \( d_v \equiv 0.027 \text{ m} \) [16].

The circular crown surface of the medial cross section of the truncated cone was calculated to respect cardiac output \( (CO_o) \) ejected during the Heart systole:

\[
S_{H,thr} \equiv 2 \cdot \pi \cdot R_{ds} \cdot z_H \quad \text{[m}^2\text{]}
\]
After replacing eq. (18) in (17) and explicit writing of the surface \( S_v \) it results:

\[
\Delta P_{H,thr} = \frac{w_B^2 \cdot \rho_B}{2} \left[ \left( \frac{8 - \frac{R_B}{d_v} \cdot z_H}{d_v} \right)^2 - 1 \right]
\]

The blood Volumetric Flow rate (Cardiac Output, CO) can be also determined as \([26]\):

\[
CO = S_{H,avr} \cdot w_B
\]

where the transversal cross-section of the crown results geometrically from:

\[
\Delta V_{H,stroke} = S_{H,avr} \cdot h = \frac{CO}{N_c} = \frac{60 \cdot CO}{N_c \cdot F_H}
\]

\[\text{(21)}\]

\[
S_{H,avr} = \frac{60 \cdot CO}{F_H \cdot h}
\]

\[\text{(22)}\]

By combining eqs. (20) and (22) it results:

\[
w_B = \frac{CO}{60 \cdot CO} = \frac{F_H}{60} \cdot h \quad [\text{m} / \text{s}]
\]

\[\text{(23)}\]

The total Heart Power, \( W_{t,H} \), based on eq. (13) is computed taking into account the losses done by throttling:

Based eq. (14), is computed the total Heart Power, \( W_{t,H} \), taking into account the losses done by throttling:

\[
\Delta V_{LL} = \frac{1}{2} \cdot V_{t,L} = \frac{V_t (1 - k_a)}{2 - t} \quad [\text{m}^3/\text{min}]
\]

\[\text{(26)}\]

The current Volume entering into the Lung at an inhalation (Stroke) is:

\[
V_t = \frac{\Delta V_{L1}}{F_L} \quad [\text{m}^3/\text{stroke}]
\]

where: \( F_L \) represents the respiration Frequency [osc / min].

\[\text{(27)}\]

Fig. 2. The schematic representation of the Lungs functioning

By combining eqs. (26) and (27) and following the notation from figure 2, it results:

\[
\left( 1 - k_a \right)^2 \frac{V_t}{2 \cdot \pi \cdot t \cdot F_L} = \frac{V_t}{2 \cdot \pi \cdot t \cdot F_L} - \pi r_i^2 \cdot h_L = \pi \cdot h_L \left( r_i^2 - r_e^2 \right)
\]

\[\text{(28)}\]

where: \( V_t \) - Lung Volume after inhalation [m³]; \( V_e \) - Lung Volume after expiration [m³]; \( r_i \) - inhalation radius [m]; \( r_e \) - radius at expiration [m].

From eq. (28) we compute:

\[
r_e = \sqrt{r_i^2 - \left( 1 - k_a \right)^2 \frac{V_t}{2 \cdot \pi \cdot t \cdot F_L}}
\]

\[\text{(29)}\]

Therefore, the Stroke of the Lung, \( z_L \) [m] (the dimensional change considered equal on the three xyz axes) is:

\[
z_L = 3 \left( r_i - r_e \right) = 3 \left( r_i - \sqrt{r_i^2 - \left( 1 - k_a \right)^2 \frac{V_t}{2 \cdot \pi \cdot t \cdot F_L}} \right)
\]

\[\text{(30)}\]

At the beginning of an inhalation at rest, the Volume of the chest increases and the air Pressure in the airway becomes lower than the atmospheric Pressure with 3÷4 mmHg, so that air enters the airways and Lungs. In the initial phase of exhalation, the inspiratory muscles relax, and the chest tends to return to the resting size. Therefore, in the Lungs and airways, the Pressure is higher by 3÷8 mmHg than the atmospheric Pressure \([18]\). Thus, the mean value of 757 mmHg and 765 mmHg, respectively, were considered in the computational scheme for the Pressures into the respiratory tract and Lungs at inhalation and expiration.

The Mechanical Work of the Lung for breathing is calculated with the relation:

\[
W_{L1} = \Delta P_{L1} \cdot \frac{\Delta V_{L1}}{F_L} \quad [\text{J}]
\]

\[\text{(31)}\]

where \( \Delta P_L = P_s - P = 765-757=8\text{mmHg} = 1066.6 \text{Pa} \). The atmospheric Pressure of \( P_s = 760\text{mmHg} = 101325 \text{Pa} \) is considered.

The total Mechanical Work of the Lung is calculated taking into account the Pressure losses done by throttling:

\[
W_{L,1} = W_{L1} + W_{L,thr}
\]

\[\text{(32)}\]
The Mechanical Work lost by throttling:

\[
W_{L,thr} = \Delta P_{L,thr} \cdot A_{L, tot} \cdot z_L \ [J]
\]  

(33)

where \( A_{L, tot} \) represents the total area of the Lungs \([m^2]\).

Similarly as in the case of the Heart eq. (19), the Pressure drop caused by the throttling of air in the Lungs, \( \Delta P_{L,thr} \ [Pa] \), is calculated by the formula:

\[
\Delta P_{L,thr} = \frac{w_{air}^2 \cdot \rho_{air}}{2} \left( \frac{8 \cdot \rho_{air} \cdot z_L}{\rho_{air} \cdot L} \right)^2 - 1
\]  

(34)

where: \( \rho_{air} = 1.153 \text{ kg/m}^3 \) - air density at 33°C; \( d_{avr,L} = 0.00769 \text{ m} \) - the weighted average of the tracheal diameters (about 18 mm) and primary bronchi (2 x 12.2 mm), secondary ((3 + 2) x 8.3 mm), segmental (8 + 7) x approx. 5.6 mm; \( w_{air} \) is the air Speed in the Lungs \([m/s]\) and it is determined as:

\[
w_{air} = \frac{F_L}{60} \ [m/s]
\]  

(35)

The total Mechanical Work of the Lungs is:

\[
W_{t,L} = 2 \cdot W_{t,L,1}
\]  

(36)

The total Mechanical Work of the Cardio-Pulmonary System is calculated based on eqs. (13) and (36):

\[
W_{t,CPS} = W_{t,H} + W_{t,L} \ [J]
\]  

(40)

The total Power of the Cardio-Pulmonary System is obtained by summing eqs. (24) and (39):

\[
\dot{W}_{t,CPS} = \dot{W}_{t,H} + \dot{W}_{t,L} \ [W]
\]  

(41)

Based on the quantified fundamental formula on Heart-Lungs interaction, the performance of the Cardio-Pulmonary System, namely the total Mechanical Work, \( W_{t,CPS} \) and the total Power \( \dot{W}_{t,CPS} \) can be expressed as function of only one Frequency (Speed), \( F_H \) or \( F_L \).

The total Lung Power, \( \dot{W}_{t,L} \), taking into account the losses done by throttling, is calculated with the equation:

\[
\dot{W}_{t,L} = \dot{W}_{t,L,1} + \dot{W}_{L,thr} \ [W]
\]  

(39)

Fig. 3. The diagrams of total Mechanical Work, \( W_{t,H} = f(F_H) \), total Power \( \dot{W}_{t,H} = f(F_H) \) and the total Entropy Source \( S_{t} [W/K] \) (for SP - Stoian Petrescu).
Fig. 4. The diagrams of the total Mechanical Work, $W_t=f(F_H)$, total Power $W_t=f(F_H)$ and the total Entropy Source $S_t[W/K]$ (for SP).

Fig. 5. The diagrams of the total Mechanical Work, $W_t=f(state)$, total Power $W_t=f(state)$ and the total Source of Entropy $S_t[W/K]$ (for SP).
Fig. 6. The diagrams of total Mechanical Work of the Cardio-Pulmonary System, $W_t=f(F_t)$, total Power $W_t=f(F_t)$ and the total Entropy Source $S_t [W/K]$ (for BB-Bogdan Borcila).

Fig. 7. The diagrams of the total Mechanical Work, $W_t=f(F_t)$ of the CPS, the total Power $W_t=f(F_t)$ and the total Entropy Source $S_t [W/K]$ (for BB).
The Source of Entropy for the Lungs is determined with the relation:

\[ S_L = \frac{Q_{irr, L}}{T_{air}} = \frac{W_{LL}}{T_{air}} \] [W/K] (43)

\( Q_{irr, L} \) is the heat caused by the friction in the lungs equal with the power consumed by the lungs \( W_{LL} \).

The total source of entropy for the CPS is:

\[ S_T = S_H + S_L \] (44)

In the respiratory region of the nasal cavity, the vascular network from mucous tunic and the venous cavernous plexus of the cornets, that are well developed at the lower level of cornet and the anterior inferior portion of the membranous nasal septum, create favorable conditions for inspiratory air heating up to 32÷34 °C [17, 18].

Applying the computation scheme for determining the total Cardio-Pulmonary System Power in two studied cases

In the paper were used the parameters measured by two persons: Stoian Petrescu (SP, 78 years old) and Bogdan Borcila (BB, 29 years old).

In all the figures, the triangle represents stationary states (standing vertical), square represents stationary (states sitting on a chair), circle represents stationary states (lying in bed).

In figures 3-5 illustrate the diagrams of the Mechanical Work and the total cardio-pulmonary Power as functions of the two fundamental parameters, \( F_H, F_L \); measured in different positions during 3 days while the person SP was ill of the flu - and the State Numbers 0, 1, 2, ..., 39) between which various elementary Processes are emphasized.

The analysis of the variation of the two parameters of the Cardio-Pulmonary System \( W_{CPS}, W_{LL} \) at the successive passage from one elementary Process to another during the 3 days when the person was suffering of the flu shows that she had higher Power consumption in the first two days of the disease when the flu had high intensity. On the third and fourth day, with the gradual healing of influenza, the total Power values of the Cardio-Pulmonary System (CPS) went down to normal. Regarding the total Mechanical Work of CPS, it was found that its variation was also reduced.

Thus, the total Mechanical Work for the person SP Cardio-Pulmonary System varies between: 9.31 and 9.40 J (on the first day), 9.35 and 9.92 J (the next day), 9.45 and 9.92 J (third day), 9.97 J (fourth day, determined for a state). The total Power oscillates between the following values: 9.16 - 9.85 W (on the first day), 7.85 - 9.51 W (the next day), 7.72 - 8.97 W (third day), 8.14 W (fourth day).

Therefore, it is noted that when SP was very ill with flu, the variations of the Cardio-Pulmonary System Power were higher, and from the second part of the third day they stabilized and returned to the limits before the illness, while the Mechanical Work had insignificant oscillations.

The study of the diagrams from figures 3-5 reveals a tendency for an increase in total Cardio-Pulmonary System Power for SP (about 22%), with increasing of the Heart, \( F_H \), and Lungs Frequencies, \( F_L \). In the case of Mechanical Work, it decreases as the Heart and Lungs Frequencies increase.

For the person SP, the total Entropy Source for the Cardio-Pulmonary System, \( S_T \), has values between 0.0153 and 0.0191 W/K. At the onset of flu (State Number 0 from figures 3-5), the Entropy Source, \( S_T \), was at the highest level (0.0191 W/K) and as the person has healed, it dropped to the normal values (0.0153 W/K) [19-25].

Based on eqs. (40) and (41), calculation was made for total values of Mechanical Work and Power of the Cardio-Pulmonary System of person BB (Bogdan Borcila) as a function of a single Speed (the Frequency of Lungs or Heart, \( F_L \) or \( F_H \)).

In figures 6-8 we represented the diagrams of the Mechanical Work and the total Power for the Cardio-Pulmonary System of the person BB. The two performance parameters were written as function of the Frequencies \( F_H, F_L \) and the Stationary State Numbers (1, 2, 3, ..., 20) in which take place the various elementary and complex Processes, for example changing the position from a bed...
to a chair, in the complex process of eating, working on the computer, etc.

The comparative study of the diagrams showing the variations in Mechanical Work and the total Cardio-Pulmonary System Power, when passing successively from one elementary or complex process to another reveals a normal Power consumption depending on the different States.

Thus, in the upright position, the muscular system of body - the striated muscles (skeletal muscles); the smooth muscles (which make up the viscera, the blood vessels and the skin); Heart muscle (myocardium) - has intense activity and hence, an average consumption until high values of Mechanical Work and Power [27, 28] (the Stationary Quantum States: 2, 7, 10, 13, 17 and 20).

In the lying position, the total Mechanical Work values are medium and large, because the center of gravity of the body oscillates vertically in the gravitational field and therefore the body exerts an additional effort during breathing (the Stationary States: 1, 6, 11, 16, 19).

The Power consumed by the Cardio-Pulmonary System in this case, when the body is relaxed, also has average and above average values in most Stationary Quantum States, except for the initial State 1.

At the same time, the diagrams illustrating the variation in Mechanical Work and total Power in stationary conditions corresponding to the seating position indicate that their values are predominantly the lowest (the Stationary States: 3, 4, 5, 12, 14, 15, 18), with the exception of States 8 and 9 in which BB has performed activities with a higher degree of mental effort at the computer. The total Mechanical Work for the BB person's Cardio-Pulmonary System varies between 9.28 and 10.07 J, and the total Power has values ranging from 2.75 to 3.42 W, depending on the body's effort in the different processes elementary and complex.

Also, the study of the diagrams in figures 6-8 reveals the trend of high increase in total Cardio-Pulmonary System of BB, with increasing of the Heart, FH, and Lungs, FL, Frequencies. In the case of the total Mechanical Work of CPS, the values have a decreasing trend with the increase of the Lungs Frequency.

Analyzing the distribution of the total Mechanical Work of the Cardio-Pulmonary System between the two components, we find that $W_{t,L}$ has the highest values (about 90%), while $W_{t,H}$ is much lower. In the case of the total Power of CPS, $W_{t,CPS}$ and $W_{t,H}$ are approximately equal.

It results that the difference is due to the greater value of Mechanical Work of the respiratory muscles that increase the dimensions of the chest cavity and of the contraction of the diaphragm muscle area, for ensuring normal breathing [18-20, 27].

The total Entropy Source of the Cardio-Pulmonary System, $S_{t}$, for the person BB, is between 0.0089 and 0.0110 W/K.

The analysis of the performance parameters of CPS for SP and BB shows significant differences between them. Thus, the total power of CPS, for SP varies between 9.85-7.72 W and the mechanical work from 9.92 to 9.31 J. For BB, the two parameters have the following values: $W_{t,CPS} = 2.75-3.42 W$ and $W_{t,CPS} = 9.28 - 10.07 J$.

The relatively large differences between the parameters of the two persons could be explained based on the $F_{t}$ and $F_{t}$ Frequencies, which are much lower for BB compared to SP: $F_{t,H,m}$ is 11.5 osc / min and $F_{t,L,m}$ is 72 osc / min (for BB) and $F_{t,H,m}$ is 24.5 osc / min and $F_{t,L,m}$ is 84 osc / min (for SP). Furthermore, the high power consumed by CPS of the SP can be caused by the processes of homeostasis that help maintain the internal environment of the human body within normal limits when it is affected by stressful conditions such as illness, heat, pain, etc. [18-20, 27].

Conclusions

The new Scheme of computation of Mechanical Work and Power of the Heart and Lungs allows the study of the variation of the two parameters of the Heart and Lungs in Stationary Quantum States, based on the values calculated with the analytical formulæ discovered that where customized to each person. The analytical expressions of total Mechanical Work and Power of the Cardio-Pulmonary System were grounded as functions of the measured parameters ($F_{t}$ and $F_{t}$), the maximum systolic pressure and person's body mass. On the basis of the quantified fundamental formula on Heart-Lungs interaction, the two performance parameters of the Cardio-Pulmonary System, total Mechanical $W_{t,CPS}$, and total Power, $W_{t,CPS}$ can be expressed as single Frequency functions, $F_{t}$ or $F_{t}$.

The calculation scheme has been verified as the results obtained by applying it are very close to those in the literature [19-25].

The diagrams of the Mechanical Work and the total Power presented above for the Cardio-Pulmonary System provide very important information on Heart-Lungs Interaction for each person (SP and BB). They also emphasize the conclusion that each person is different from each other in terms of Heart-Lungs interactions on the one hand and the Cardio-Pulmonary System - the whole body on the other. Such information could be particularly useful if a person needs a pacemaker or even an artificial Heart. The two devices could now be designed based on personalized data using diagrams obtained by any person [7-15] before they needed such artificial devices to save their lives.

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