IGCRE 2014
1st Joint Iran & Germany Conference on
Renewable Energy
14-RENE-125

September 9-10, 2014
Shahid Beheshti University, Tehran, Iran

Energy harvesting with piezoelectric for implantedmedical device

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***Abstract*—One of the implant medical issue that run on batteries is energy supply. Human body as renewable energy has huge source of energy, which can help to decrease costly and tedious replacement. This paper present a micro–scaled power generator for implant medical device that harvest energy from the contraction of respiratory muscle by using piezoelectric. after muscle selection and its force computing, the software modelling developed to predict output power system. software simulation indicate that this generator concept can generate 7 μW averagely during respiration.**

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I. Introduction

One of the most amazing achievements in health care is the usage of Implant Medical Devices (IMDs) such as pacemaker, hearing aid, etc. Among them, IMDs have the vital role in promotion of patient's quality of life and achieving comfort conditions. These devices are usually active and require energy which should be stored in batteries. Unfortunately, due to the limitations in technology, batteries can only store a specific amount of energy which is not enough for a long term operation. Therefore, this encounters source of power limitation which in turn requires battery replacement. The replacement of battery require frequent, costly, surgeries with increased risk of complication. One solution is to replace the non–rechargeable (primary) batteries with rechargeable ones but should provide a practical way for its charging. Thereby, it has been so significant to use energy harvesting systems that extend battery life time, decrease or eliminate operation times and provide continuous power.

Since IMDs are located inside the human body, we should seek the sources of energy that are inside the body. Human body itself is a major source of energy which can be regarded as renewable energy source. However, a man requires the energy of the body for its own living activities. Thus we should seek the ways that can harvest a small amount of energy which does not result into patients' suffering. The energy obtained from human body has a very low power but, it is found to be suitable for battery charging. This strategy extends the battery life time; hence, less surgery is needed which is very important

There are many different energy source inside the human body; namely a) chemical energy, b) thermal energy, and c) mechanical energy. Chemical energy is the free energy due to glucose oxidation. Micro–biofuel cell convert chemical energy to electricity. Thermal gradient is another source of energy used to energized low–power devices. Gained power from thermal energy of human body is related to temperature distribution and may differ case by case and also by different disease. Mechanical energy such as human body motion and air flow respiration, compared to another sources of energy is more popular and useful to be harvested. There are many different ways for converting mechanical energy to electricity among which usage of piezoelectric materials is more suitable for our purposes. These devices are known to be direct energy converters; that means they do not need any intermediate operation for energy conversion. In other words, the mechanical motion such as muscle contraction can be directly converted to electricity by such materials.

Muscle contraction is capable to supply required power for IMDs. But we can not implant a piezoelectric device in all the human body; because for continuous charging we need some specifications. In the present requirement, muscles are divided into continuous and non–continuous motion categories. Muscles with continuous movement are heart, vessel and thorax. Other muscles such as leg and hand have non–continuous motions. Comparing the above mentioned non–stop ones, thorax muscles seems to be the best choice compared to the others since they are the strongest.

In 2009, Elfrink et al. [1] studied and manufactured a Lead Zirconate Titanate (PZT) micro generator that could generate $60\,\mu\mathrm{W}$ under 2g acceleration at $572\,\mathrm{Hz}$ resonant frequency. Meiling et al. [2] in 2010 presented a piezoelectric micro generator whose power output was 1 to $2\,\mathrm{mW\,cm^{-3}}$; That amount of energy is completely enough for the present purposes. In 2013, Jun Zhao et al. [3] considered piezoceramics generator elements. It has been proposed for improving the electricity generation performance and used d_{33}- mode PZT that can be used for energy harvesting in roads and bridge.

In 2003, Ratnovsky et al. [4] considered and analized relative contribution group pf respiratory muscle to global lung ventilatilation throughout arange of activity in healthy subject. After two years, Retnovsky and Elad [5] developed a two–dimensional model of human trunk. They predicted force generated by respiratory muscle with measurement of electromyography (EMG) signal near the skin. After that, Awrejcewicz and Luczak [6] studied a a two–dimensional model of rib cage with finite element analysis for recognizing of stress distribution in two cases. In 1988, Haustler et al. [7] presented rolled polyvinyldene fluoride (PVDF) film to harvest energy from motion of breathing. The device, produce 17 microwatt that connected between sequential ribs in a canine. In 2007, Lewandowski et al. [8] studied piezoelectric device that attached between muscle and tendon to convert expansion/contraction of muscle to electricity. That device was predicted to generate 690 μW of power when deposited to the gastrocnemius muscle.

The study of muscles with continuous motions shows that the respiratory muscles have the most potential to continuous and reliable power generation compared with other cardiovascular muscles. They have the potential of producing a high output power and energy which is enough for covering all our needs for IMDs. In the present study, we propose a new design of PZT device for power generation that could be enough for charging (or even elimination of) implanted batteries. To do this, we first analyze the rib cage structure and determine the force and displacement of the rib cage. Second, we present a proper geometry for installing the PZT device. Finally, with considering piezoelectric movement, we determine the obtained output power of the PZT by solution of its governing equation.

II. Design study

The power demand for IMDs is shown in table I. A proper generator (or storage device) should be able to deliver the needs shown in this table. It is known that respiration muscle movements have the potential for delivering such demands. On the other hand, piezoelectric material are one of the best choices for converting the mechanical movement to the required electricity. In this section, the piezoelectric property is discussed and its mathematical formulation is given. Then the movement of rib cage is studied in details and the potentially exerted force and movement of each rib is discussed. Finally a proper design for power generation is proposed.

TABLE I
ENERGY DEMAND [9]

medical implant	power consumption, μW
pacemaker, cardiac defibrillator	10
hearing aid	100-2000
neural recording	1000-10,000

A. Piezoelectric Properties

Piezoelectric effect manifest itself as transfer of electric to mechanical energy and vice versa. It is present in many crystalline materials such as quartz, Rochelle salt and lead titanat zirconate ceramics. The piezoelectric effect can be seen as a linear combination of elastic and dielectric contribution.

$$D = eS + \epsilon^s E \tag{1}$$

$$T = c^E S - e^t E \tag{2}$$

In these equations S and D present vector of mechanical strain and dielectric displacement, respectively with superscript t and e mean at constant stress and electric field. Also c^E and ϵ^s are called the mechanical stiffness coefficient and permittivity matrix, and e is piezoelectric matrix.

The temperature, T is assumed to be constant due to the operating conditions of the IMD. If the temperature is not constant, other thermally induced effects such as elongation and pyroelectricity can occur and the governing equations should be modified accordingly. the electric field is related to electrical potential (eq 5), and the mechanical strain to the mechanical displacement u, where in the Cartesian coordinates. The elastic behavior of piezoelectric media is governed by Newton's law:

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla . \sigma \tag{3}$$

$$S = Bu \tag{4}$$

$$E = \nabla V \tag{5}$$

Where ρ is density of the piezoelectric medium, whereas the electric behavior is described by Maxwell's equation considering that piezoelectric media are insulating:

$$divD = 0 \tag{6}$$

Equation (1–6) constitute a complete set od differential equations which can be solved with appripriate mechanical (displacement and force) and electrical (potential and charge) boundary conditions.

B. Force of Muscle

For an accurate design, the force of respiratory muscles should be determined. Ratnovsky et al. [4] worked on this matter and determined the exerted force by means of EMG test. Respiration muscle which are best fitted for the present study are internal intercostal, external intercostal, diaphragm, sternomastoid, etc.

Respiratory muscles consists of two type; namely inspiratory and expiratory muscles. external and internal intercostal are attached to the ribs at different places and their fibers are oriented in different directions. As a result, contraction of the external intercostals elevates and contraction of the internal intercostals depressed the ribs. Relationship of the internal and external intercostal muscles is shown in figure 1.

EMG data [4] shows that external intercoastal muscle generate more power as showed in figure 2. The forces of muscles are crucial for the present study; for this reason we use Hill's model [10] to obtain these forces. In this model, for each muscle forces are composed of three elements that represents muscle mechanical response and are contractile element (CE) and two nonlinear spring elements in series (SE) and in parallel (PE). Contractile element represents the forces of active fibre

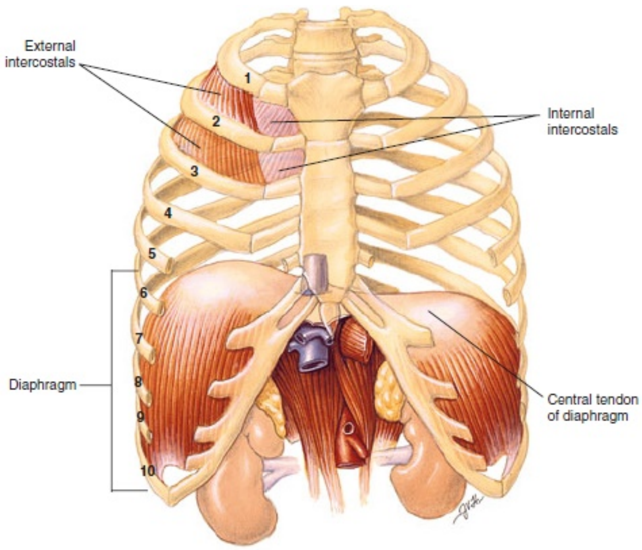

Fig. 1. location of external and internal intercostal muscles

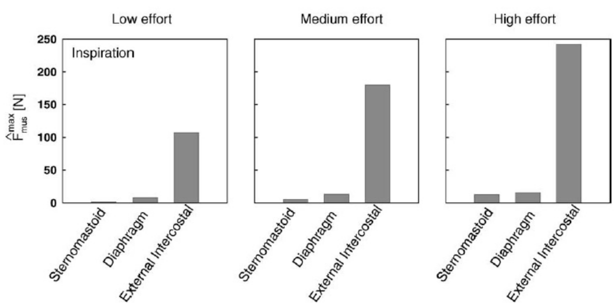

Fig. 2. Comparison between muscle force

or connective tissue that surrounds the contractile element. The parallel element represent the passive force of connective tissue and represents the muscle mechanical response. The series force represents the forces of tendon that has soft tissue response and provide energy storing mechanism These forces are formulated as follows:

$$F_{CE} = F_{SE} \tag{7}$$

$$\Delta L_{SE} = \Delta L_{PE} - \Delta L_{CE} \tag{8}$$

$$F_{\text{mus}} = F_{PE} + F_{SE} \tag{9}$$

Here, F_{mus} is the total muscle force, F_{CE}, F_{SE} and F_{PE} are the forces dveloped by the contractile, series and parallel elements, respectively; and ΔL_{CE}, ΔL_{SE} and ΔL_{PE} are the respective length changes measured from the rest condition.

Force displacement relationship of the elastic elements are

TABLE II
PARAMETER OF EXTERNAL INTERCOSTAL MUSCLE BY HILL'S MODEL

parameter	definition	unit
$F_{PE\max}$	58.8 K_{pi}	N
$F_{SE\max}$	75.16 K_{pi}	N
$\Delta L_{PE\max}$	1.305 K_H	cm
$\Delta L_{SE\max}$	0.015 K_H	cm
SH_{PE}	8	
SH_{SE}	2.7	
K_{pi}	$\frac{P_{\max}(i)}{P_{\max}}$	
K_H	$\frac{H_i}{H_r}$	

assumed to be exponential:

$$F_{SE} = \left(\frac{F_{SE\max}}{\exp(SH_{SE}) - 1}\right)\left(\exp\left(\frac{SH_{SE}\Delta L_{SE}}{\Delta L_{SE\max}}\right) - 1\right) \tag{10}$$

$$F_{PE} = \left(\frac{F_{PE\max}}{\exp(SH_{PE}) - 1}\right)\left(\exp\left(\frac{SH_{PE}\Delta L_{PE}}{\Delta L_{PE\max}}\right) - 1\right) \tag{11}$$

where $F_{PE\max}$ and $F_{SE\max}$ are the maximal force that can be generated by the parallel and series elements. $\Delta L_{SE\max}$ and $\Delta L_{SE\max}$ are the maximal length changes of the elastic elements, and SH_{PE} and SH_{SE} are the shape parameters of the parallel and series elements. The parameter definition of external intercostal muscle is given in table II.

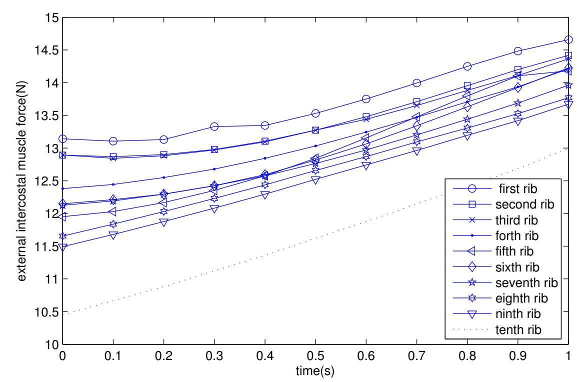

Fig. 3. External intercostal force for ten ribs

Lung ventilation is determined variation in oriantation of the ribs (table III). Thus, we can developed this variation to force muscle. With this assumption force variation of external intercostal muscle indicate with time (figure 3).

From figure 3 it can be seen that the force of the first rib is higher than the others; hence, this rib can generate more power. For this reason, in the present study, we chose the first rib for power generation.

The variation of F_{EI} with time was fitted to a second–order curve for the model simulation.

The instantaneous force of each muscle unit was evaluated by Hill's model. The external intercostal muscle force in

TABLE III
VARIATION OF THE RIB ANGLE WITH VOLUME OF LUNG [11]

% VC	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}
0	62.4	60.38	60.4	56.6	53.7	55	5.85	51.8	50.8	44.8
10	62.1	60.2	60	57.05	54.21	55.43	55.3	52.96	51.95	46
20	62.3	60.44	60.3	57.8	55.12	56	56	54.21	53.21	47.2
30	63	61.06	61	58.75	56.4	56.9	56.9	55.56	54.56	48.6
40	64.14	62.1	62	60	58	58.13	58	57	56	50
50	65.83	63.52	63.52	61.5	60	59.8	59.4	58.6	57.6	51.6
60	68	56.36	65	63.26	62.5	61.75	61	60.2	59.23	53.2
70	70.67	67.58	67	65.27	65.34	64.1	62.9	62	60.95	55
80	73.9	70.2	69.4	67.56	68.5	66.8	65	63.8	62.84	56.82
90	77.56	73.23	72.06	70	72	69.9	67.36	65.8	64.8	58.8
100	81.27	76.46	75.6	73.4	73	73.6	70.3	68.2	67.2	61.2

direction x and y are

$$F_{EI_x} = F_{EI_i}(t)\cos(\beta_{EI_i(t)}) \tag{12}$$

$$F_{EI_y} = F_{EI_i}(t)\sin(\beta_{EI_i(t)}) \tag{13}$$

in which t is the time and $\beta_{EI_i(t)}$ is the angle between the external intercostal muscle and the horizental surface. F_{EI_x} and F_{EI_y} are the force of the external intercostal in the x and y directions, respectively.

Schematic of rib and Coordinate system on it present in figure 4.

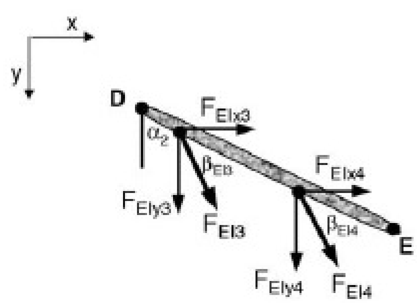

Fig. 4. schematic of rib and its coordinate

C. The configuration of the present piezoelectric device

In [12] it has also been suggested that nanogenerator can be made of piezoelectric nanowalls rather than nanowires. Then, the geometry selected is rectangle cubic which is $0.15\ \mathrm{cm}^3$ volume (figure 5). In addition, it is interesting that experiments [13] have confirmed that vertical compression and lateral streching give the best results, consistently with [12].

According to loading and poling direction, mode of operation is 33–mode. In addition, we should embed the device in human body that scavenge all energy that exist.

In coastal margine, some joint have no movement whose call costochondral joints_they between the coastal cartilage and a rib. So, two side of piezoelectric device attach on the first and second joints of thorax and applied the force with a foreign object.

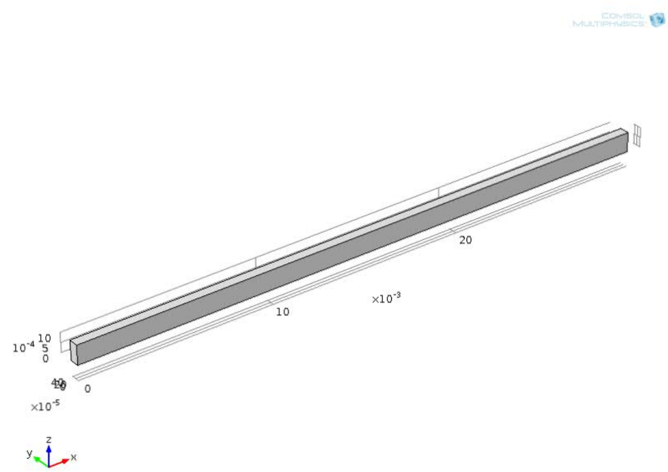

Fig. 5. Geometry of micro–generator

III. SOFTWARE MODELING

The piezoelectric device model (equations (3) to (6)) is solved using finite element–based commercial software COMSOL Multiphysics®. Figure 5 shows the geometry of the micro–generator. For numerical simulation, a uniform mesh grid is generated to minimized the computational cost while maintaining the accuracy (figure 6).

Applied force resulted by external intercostal muscle between the first and the second rib are shown in figure 7. In modeling we choose PZT_5A, because it has high compatibility with body and high output power.

IV. RESULT AND DISCUSSION

Fig. 8 indicate piezoelectric displacement after $0.1\,\mathrm{s}$ of respiration. As figure 8 shows, the applied force is normal to the beam surface and the two ends of the generator is fixed without any movement.

As we can see in figure 9, potential of the piezoelectric material increases from zero to $2\,\mathrm{V}$ during inhale when the loading increases. Figure 10 illustrate the output power of the device. This power has a peak about $17\,\mu\mathrm{W}$ but the average output power is $7.3\,\mu\mathrm{W}$. As we expected, power generated

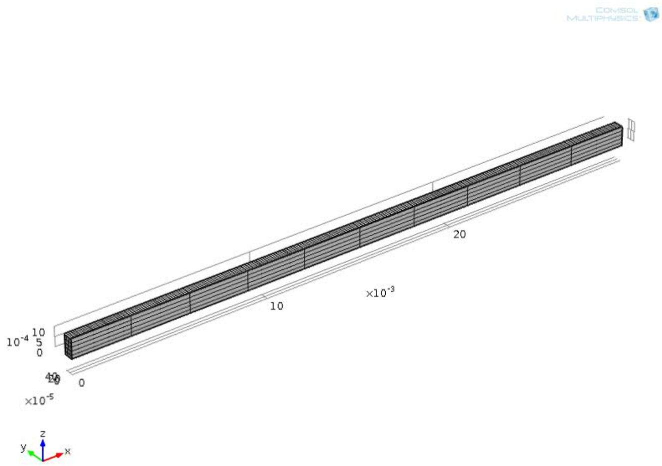

Fig. 6. force applied by external intercostal muscle

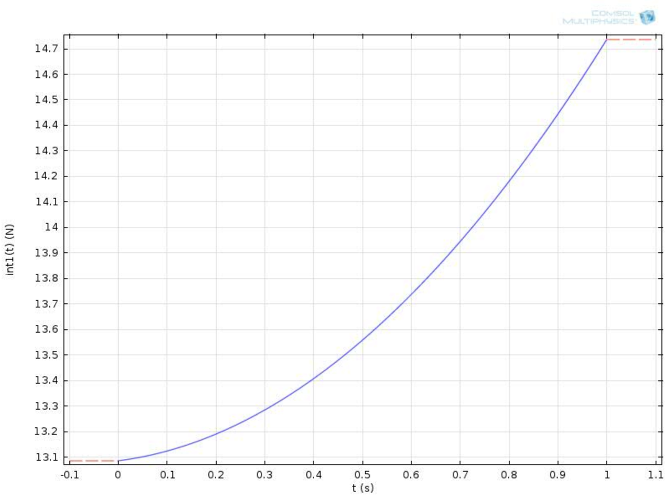

Fig. 7. force applied by external intercostal muscle

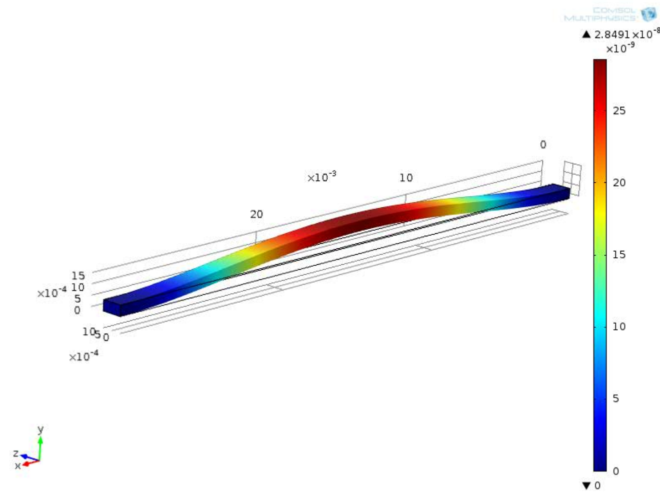

Fig. 8. piezoelectric displacement

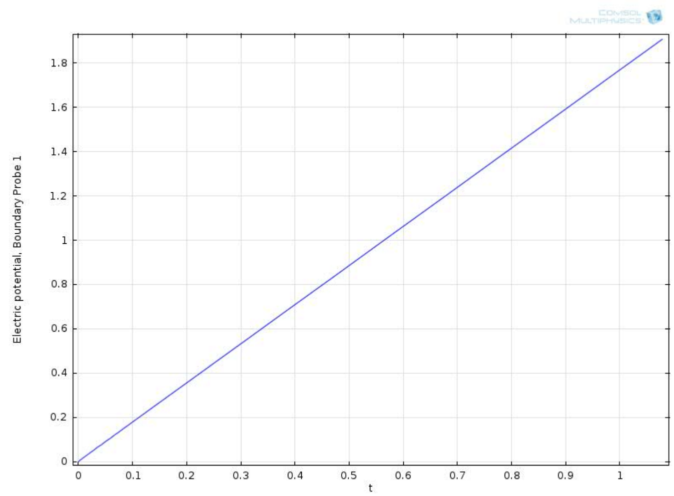

Fig. 9. potential variation during loading

during respiration is enough to run implant medical device during one single respiration.

V. CONCLUSION

Numerical simulation was conducted to study piezoelectric material for constructing a mico–generator. The result of the present study shows that micro–generator devices based on piezoelectric materials are able to generate enough power for charging implanted batteries. This idea will increase the battery life time which in turn decreases the number of surgeries required for replacement of the IMD's batteries.

ACKNOWLEDGMENT

The authors would like to thank Ms. Pardis Nafarzadeh for her professional advice and remarkable guidance about human physiology.

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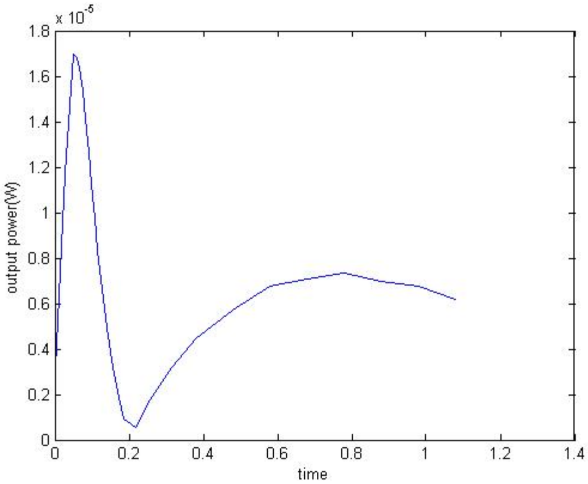

Fig. 10. output power during respiration

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