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Comparing Three Methods for Controlling Temperature in Order to Optimize Energy Performance and Consumption in a Novel Thermoelectric Vaccine Carrier

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ABSTRACT

Introduction: Millions of bucks are annually wasted as a result of improper preservation of vaccines. One reason may be visualized in limited availability of the equipment for an entire cold chain. In this regard, an efficient thermoelectric carrier may be introduced so as to carry vaccine in parts of cold chain. Considering limited power source in a portable set, optimization of thermoelectric system performance is of a great importance in order to achieve an efficient cooling. The present paper aimed at optimizing the thermoelectric system by altering temperature control method to be adopted in a novel thermoelectric vaccine carrier.
Methods and materials: In order to regulate internal temperature, three temperature control methods (i.e. (a) ON/OFF method; (b) ON/OFF with fan performing during OFF status; (c) High-voltage/Low-voltage method) were determined in a thermoelectric vaccine carrier in terms of voltage consumption control. Afterwards, power consumption and internal temperature of the set were measured in the three methods and compared by t-test in SPSS 20.
Results: Power consumption and the time needed for reaching favorable temperature from the onset until the uniform status were identical in all the methods (38.5 W and 32 min, respectively). However, significant differences ($P<0.05$) were detected in power consumption in stable status(13.47, 9.5, and 7.3 W in (a), (b), and (c) methods, respectively).
Conclusion: The results obtained from the present study indicated the method (c) to be the most efficient despite higher performance of the method (b) than (a). The method (c) is capable of reducing power consumption for 45.8% compared with conventional ON/OFF methods.Therefore, the method (c) is recommended for optimization of power consumption and performance boost in thermoelectric vaccine carrier and other similar portable sets.
KEYWORDS: vaccine carrier, thermoelectric, optimization, power consumption.

1- INTRODUCTION

Immunization against a disease may not be prosperous unless it uses effective vaccines. Preservation of biologic effect of vaccines necessitates cold chain, a set of stages which should be met in order to keep desired temperature from vaccines production to consumption. (Samant et al., 2007)If the materials are exposed to unfavorable temperatures, they will have their efficacy and shelf life reduced; such vaccines are no longer applicable and should be discarded imposing a heavy cost to societies. (Weir et al. 2004)The UK National Patient Safety Agency (2010) reported that circa 50 million doses of children's vaccines decayed from 2005 to 2009 due to cold chain problems. Relieving such problems is based upon rendering reformations in the chain as the main hurdle is undesired temperatures in some parts of the chain. In this regard, Matthias et al. (2007) pointed to necessity of education and supervision on vaccines transport along cold chain.

Vaccine carriers and cold boxes are important components of cold chain placed in last part of the chain. Theyare, in fact, insulating boxes whose cold is kept by ice bags and foam pads. They will provide desired temperature for vaccines from 2 days to a week if they are provided standard criteria. However, they will not be dependable for preserving vaccines once they are opened; this is an important limitation for them. Majority of the sets, on the other hand, are not temperature-adjustable and consequently, frozen ice bags are essential along with them. (World Health Organization/WHO, 2004)

Therefore, a complementary set in cold chain looks to be a very urgent requirement. The" Vaccine storage and transporting device, with continues cold"[P]has been designed to fill this need. Despite being light and portable, the set is capable of providing desired temperature for majority of vaccines during transport

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eliminating the effect of temperature variations on vaccines' performance even in case the door is opened. The set may, thus, be used as a complementary set in parts of cold chain. (Mojabi et al., 2012)

The set is dependent on thermoelectric system. Compared with compressor systems, thermoelectric ones make lower noise, are lighter, environment-friendly, and economical for mass production. In addition, they may be produced in lower volumes and it can be battery-operated so that they serve wider applications. (Min& Rowe, 2006;Vián&Astrain, 2009; Rowe 2011; Sadur et al., 2008; Rawat et al., 2012)

Desired thermoelectric coolers have prominent advantages such as accurate temperature control. However, the cost varies in terms of temperature control method they adopt. Majority of available sets utilize ON/OFF control method to control temperature which is the simplest and cheapest. In this method, a temperature range with two high and low thresholds is defined for the set. The set starts with maximum voltage until the internal temperature reaches the low threshold (V1=maximum). Afterwards, it is turned off until the temperature gets to high threshold (V2=0). This is a continuous cycle. The main problem of the method, however, is that when the set is turned off, the stored heat in hot side of heat exchanger returns to the cooling environment by forming a thermal bridge. As a result, the set should start again and consume more power leading to higher power consumption and reduced coefficient of performance. (Astrain et al., 2012)

In order to prevent such a loss, thermoelectric refrigerator manufacturers have recommended other control methods such as PID, Different Level Voltage, and Constant Voltage. Nevertheless, the recommendations caused higher prices for the finished goods. That's why the ON/OFF systems have retained their place in market. (Astrain et al., 2012; Bell, 2008)

Considering limited power source in a portable set, optimization of thermoelectric system performance is of a great importance in order to achieve an efficient cooling. Besides, complicated carrier systems not only cause higher costs but make it more unlikely to meet WHO's standards (2010) as well. Therefore, the present study aimed at optimization of thermoelectric system by changing temperature control method and comparing three simple methods in order to offer the most optimum power consumption with lower complexity and cost for" Vaccine storage and transporting device, with continues cold"[P] as a novel thermoelectric vaccine carrier.

2- METHODS AND MATERIALS

A thermoelectric vaccine carrier with a 4.2 lit internal volume was designed which consisted of an aluminum piece with a same area as the module's, thermoelectric module, aluminum heat sink with a 0.5°C/W heat resistance and a 2.5 W fan.

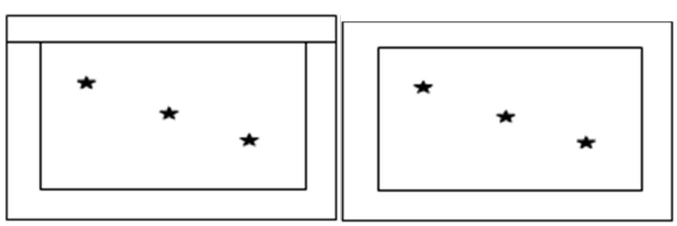
In order to adjust internal temperature, three temperature control methods were launched and determined in terms of voltage consumption control:

(a) Once the internal temperature reached low threshold, the thermoelectric system was turned off until temperature reached high threshold. Then, the system was turned on again and the cycle went on (conventional ON/OFF method).

(b) Once the internal temperature reached low threshold, thermoelectric modulewas turned offwhile the fan was still working, until the temperature reached high threshold. Then, the modulewas turned on again and the cycle continued.

(c) Once the internal temperature reached low threshold, thermoelectric module worked with minimum voltage rather than being turned off. Once temperature reached high threshold, the set worked with maximum voltage again and the cycle continued.

In order to track temperature, three sensors (SMT160) were placed in three parts inside the set according to WHO protocol (2010) for determination of vaccine carriers' standard temperature; the figures obtained from the sensors were averaged and the resulting figure was considered the internal temperature of the set (Figure 1).



AB

Figure 1.sensors placement: A) Side view; B)Top view

All the evaluations for the control methods were performed in room temperature (25°C). Before each experiment, the set was placed at this temperature for 24 h in OFF mode with open door according to WHO protocol (2010). The low and high thresholds were set to be 5 and 7°C, respectively. Next, power consumption and internal temperature were evaluated for 4 h with 1 min intervals for all three control methods and power consumption was calculated as follows:

$$P = RI^2$$

$$P = \frac{W}{t}$$

$$P = VI = \frac{V^2}{R}$$

$$P_s \times \frac{Time}{60\ min} = P_t$$

The obtained data were subjected to statistical analyses by SPSS 20 and t-test at 0.05 as significance level.

3- RESULTS

Power consumption and the time needed for reaching favorable temperature (5°C) from the onset until low threshold were identical in all the methods where it took 32 min to reach 5°C and power consumption was 40 W at this time.

However, once the set reached 5°C and started its continuous cycle, power consumption and temperature tolerance fluctuated. Power consumption in continuous status were 13.47, 9.5, and 7.3 W for the methods (a), (b), and (c), respectively; the figure were found to be significantly different ($p<0.05$). it took 2, 8, and 19 min to reach from low threshold to high threshold in continuous state for the methods, respectively (Figure 2).

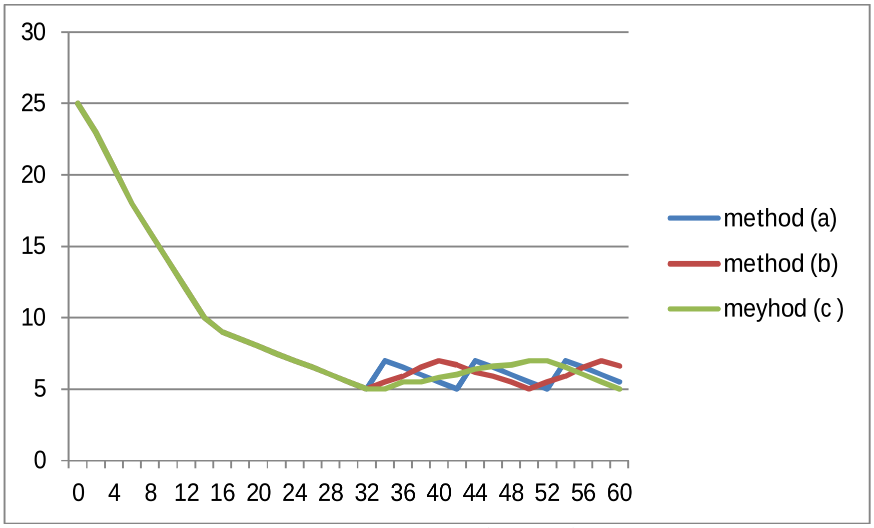


Figure 2.temperature-time chart in thefirst 1 h for all three methods

4- DISCUSSION

Keeping cold chain between 2 and 8°C from vaccine production to consumption plays a vital role in efficacy and shelf life of vaccines.(Weir et al. 2004; Samant et al., 2007) According to the figures put forth by WHO, 50% of the vaccines produced all around the world are wasted.(Guichard et al., 2010) In a study performed in 2002, vaccines loss in public vaccination program of the United States of America was estimated to be 2.6 reaching even 5% in some states.On the basis of another figure, 618 million dollars were wasted in 1998 in America during vaccine distribution in governmental sector. (Setia et al., 2002) So, thermoelectric vaccine carriers are necessary as complementary sets for cold chain.

The present study was performed to optimize thermoelectric system by changing temperature control method to be used in a novel thermoelectric vaccine carrier. Two recommended methods to increase thermoelectric system performance were studied and compared with the conventional ON/OFF method which is the cheapest, simplest, and most applicable system in market.

The methods (b) and (c) were used in the present study because they do not cause higher complexity and final cost in thermoelectric system unlike other methods such as PID, Different Level Voltage, etc.

The results acquired from the present study showed that both (b) and (c)methods, with the latter showing better results, lead to lower energy consumption and higher performance compared with the method (a). By use of the method (c), energy consumption had a 45.8% reduction with almosttwice performance. In other words, cooling time can be almost twice with the same amount of power by use of the method (c) instead of (a).

In the method (c) design, minimum electrical current was decided to be the one in which thermoelectric act solely as a heat insulator preventing from thermal convection. In other words, in minimum current, thermoelectric neither uses power for making the chamber cooler nor allows the outer heat to infiltrate in through thermal convection. The heat thermoelectric takes from the chamber is measured as the sum of heat transfer caused by thermoelectric effect, the heat caused by thermal conductance, and ohmic heat caused by electrical current.(Lineykin& Ben-Yaakov, 2007)

Relation (1): $q_c = \alpha_m T_c I - \frac{\Delta T}{\Theta_m} - \frac{I^2 R_m}{2}$

Where I is the electrical current passing from thermoelectric, Tc is the temperature of cold side (5°C here), and ΔT is the temperature difference between hot and cold sides. Furthermore, R_m, Θ_m and α_m stand for electric resistance, thermal resistance, and energy conversion coefficient, respectively which are derived as follows(Lineykin& Ben-Yaakov, 2007):

$$\alpha_m = \frac{U_{max}}{T_h}$$

$$R_m = \frac{U_{max}}{I_{max}} \frac{T_h - \Delta T_{\max}}{T_h}$$

$$\Theta_m = \frac{\Delta T_{\max}}{I_{\max} U_{\max}} \frac{2T_h}{T_h - \Delta T_{\max}}$$

Where $\Delta T_{\max}$ stands for maximum possible temperature difference between cold and hot parts of thermoelectric provided T_h is the temperature of hot side. Moreover, I_{max} and U_{max} are the current and DC voltage of thermoelectric at the maximum temperature difference$\Delta T_{\max}$, respectively.(Lineykin& Ben-Yaakov, 2007)

In relation (1), q_c (amount of heat dissipated by thermal load)need to be zero to have thermoelectric only as an insulator. Therefore:

$$\alpha_m T_c I - \frac{\Delta T}{\Theta_m} - \frac{I^2 R_m}{2} = 0$$

Consequently:

$$I_{min} = \frac{\alpha_m T_c \pm \sqrt{\alpha_m^2 T_c^2 - \frac{2\Delta T R_m}{\Theta_m}}}{{R_m}^2}$$

The following was cited for 25°C in the adopted thermoelectric datasheet:

$$U_{max} = 14.4\,V$$
$$I_{max} = 6.4\,A$$
$$T_h = 298\,K$$

Therefore:

$$I_{min} = 0.85A\ ,14.48A$$

Needless to say, power consumption at 14.48 A is far higher than that at 0.85 A. Thus, the current 1 A was chosen as minimum current for the present setup which equals to 5 v.

In their computational study based upon a recommended mathematical modeling system, Astrain et al. (2012) compared ON/OFF method with two other ones (Idling voltage and Constant voltage). They offered ON/OFF method to be replaced by Idling voltage method which was similar to our (c) method with 40% reduction of power consumption and twice performance. What they found was consistent with our results.

Considering application of the set in cold chain, we strived in meeting some criteria proposed by WHO as follows:

- In selecting control methods, the simplest method was chosen to prevent complexity.
- As WHO proposed desired temperature for preservation of vaccines to be 2-8°C, the present study adopted 5°C as the reference temperature.
- 3 sensors were placed inside the set according to the protocol proposed by WHO in order to track internal temperature of the set (Fig. 1).
- Also, according to WHO protocol, the set was placed at ambient temperature for 24 h in OFF mode with open door.

Furthermore, evaluations were performed for all three methods in the same manner.

Taken together, although ON/OFF system reduces final price of the equipment, it imposes limitations in terms of long-term costs and limited power source in portable sets. Astrain et al (2012) showed that in ON/OFF system, 56.9% of overall power consumption is used to compensate for the heat dissipated to the chamber in Module Off mode. It is also noteworthy that complicated systems reduce long-term costs; however, they are not welcomed by customers due to increased primary costs. Additionally, such methods are not recommended in a vaccine carrier because of WHO's disagreement with complication of vaccine transport systems. Therefore, the methods recommended here, notably (c), may be regarded as the best methods to be used in novel vaccine carriers and other similar equipment because they reduce power consumption and do not increase complexity and primary cost.

5- Conclusion

High-voltage/Low-voltage methodis recommended to be adopted instead of ON/OFF method in all thermoelectric devices due to lower power consumption, higher performance, simplicity, and proper cost.

Furthermore, the method is considered a favorable method for vaccine preservation and transport set with continuous cold. This control method is especially useful to be used in portable devices due to power source limitation in such devices.

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