ARTICLE

Determination of the Postmortem Interval Using Fiber Bragg Grating Sensors

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ABSTRACT

Fiber Bragg grating (FBG) sensors are often used in monitoring activities and to ensure that environmental parameters satisfy industrial requirements. They offer crucial safety measures in the early detection of hazards due to their greatly reduced size, low weight, flexibility, and immunity to electromagnetic interference. These characteristics make FBGs suitable also for use in relation to the human body for *in vivo* measurements and long-term monitoring. In this study, recent developments are presented with regard to the utilization of these sensors to measure the so-called post-mortem interval (PMI). Such developments rely on numerical simulations based on the Matlab software and monitoring of the rectal temperature, which is one of the main parameters for estimating the PMI. First, the Matlab software is used to solve the Henssge equation for different ambient temperatures and for different body masses; then a Bragg grating sensors is used for post-mortem dating. The results and their accuracy are discussed.

KEYWORDS

Fiber bragg grating; temperature sensors; Henssge's nomogram; post-mortem interval; biomedicine

1 Introduction

The advent of fiber-optic communication has revolutionized nearly all aspects of communication technology, it is meant that there is a periodic change in the core's refractive index. was noticed in germanium-doped fibers by Hill et al. [1]. However, a renewed interest has risen with the demonstration of the side writing technique by Meltz et al. [2] almost ten years later; optical fibers can change property when they are exposed to intense optical interferences patterns. This photosensitive effect can be used to induce periodic modulation in the refractive index along the fiber length. This periodicity produces an intra-core in the fiber Bragg grating (FBG). It is relevant to mention that the principal property of FBG is that they reflect light in a narrow bandwidth that is centered about the Bragg wavelength popularly known as photonic band gap (PBG). This property makes them the device of choice for various applications both in optical telecommunications networks and in the biomedical field [3–5].

In the last decade, Fiber Bragg Gratings (FBGs) have shown a great potential for applications in the field of medicine [6–10] due to their prominent advantages such as their small size, biocompatibility, chemical inertness, immunity to electromagnetic interference (EMI) and multiplexing capability [6]. These characteristics make them suitable for human body uses that adapt to the sensor material so that they can

be used for *in vivo* measurement and can be left for long-term monitoring [6]. Grating based sensors are well known technology for structural health monitoring (SHM) in the area of civil and aerospace [11–15]; however, investigations for their use in the field of medicine are fairly recent. Presently, FBGs sensors are widely used for detecting various parameters such as strain, pressure, temperature, vibration, curvature and refractive index of the surrounding material even in high magnetic and electric field environments. They can serve as diagnostic purposes in diverse areas of health care such as biomechanics, cardiology, gynecology, very low temperature monitoring and immunosensing to name a few [6,7,9,16,17].

They also offer high-performance, in comparison to standard technologies like electrical strain gauge (ESG), piezoelectric, resistive or other solid-state sensing, either for measuring physical parameters or for performing high-sensitivity biochemical analysis. In view of these aspects, it can be predicted that this rapidly evolving technology can provide much better and effective solutions for various biomedical applications and be an integral part of the futuristic health care system. In this work, we present a study for post-mortem dating using a fiber Bragg grating sensors. Our method is based on a numerical simulation using the Matlab software, of the evolution of rectal temperature, which is one of the main parameters for estimating the post-mortem interval (PMI). It is interesting to note that the objective is the exact determination of the body temperature, which informs us about the time of death.

Determining the exact time of death is complex in that the process must take account many environmental, physical and biochemical factors that affect the body immediately after death. Various methods are used to estimate the time since death such as the entomological method [18–21] and thermometric method.

This latter dating method back to the mid-19th century, but the most important result of research in this area took place in the 20th century, when a nomogram reading the time of death was developed by Henssge in 1988 [21].

The Nomogram Method (Fig. 1) is based on a single measurement of the rectal temperature, but subject substantial errors that may result from individual characteristics, daytime temperature fluctuations, ambient conditions or differences in the depth at which the temperature is taken [22–24].

In response to these shortcomings, a model based on a heat flow modeling (principle of the elements finished) was proposed by Mall et al. [25,26], however, the level of accuracy of the model requires a perfect description of the environment of the body, especially regarding transfers energy by radiation, very difficult to obtain inconvenient.

Recently new promising approaches have been tested [19,27] although these methods are employed to delimitate the PMI in everyday forensic work, there are still great inaccuracies and limitations in many cases. Therefore, novel methods for time of death estimation that comply with the requirements of practice are still of high demand.

2 Theory and Modeling

2.1 Theory of Post-Mortem Dating

In a significant work, Henssge [21] modeled a bi-exponential function, which varies according to the weight of the individual as Eq. (1)

$$\frac{T_{Rectal} - T_{Ambient}}{37.2 - T_{Ambient}} = 1.25e^{-kt} - 0.25e^{-5kt} \tag{1}$$

where t represents the time of death and k is a parameter dependent on the individual's M mass (kg) given by Eq. (2)

$$k = \frac{1,2815}{M^{0,625}} - 0,0284 \qquad (2)$$

Claus Henssge has created an abacus system to determine, based on body temperature, ambient temperature and individual mass, the likely time of death [28].
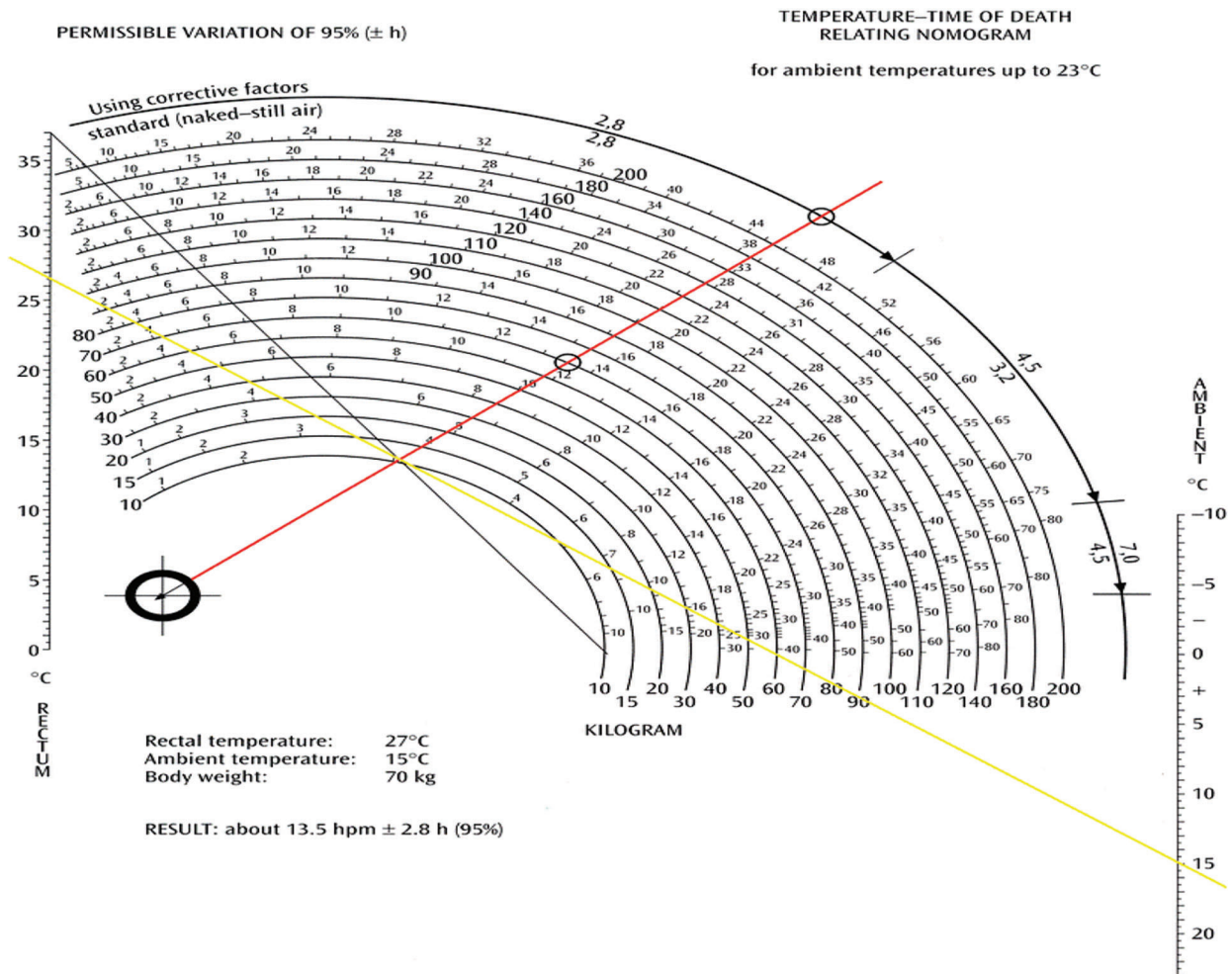

Figure 1: Application of the Nomogram-Method [22]

2.2 Temperature Sensitivity of Fiber Bragg Grating

As well known, the Bragg wavelength, λ_B, which is the center wavelength of light back reflected from a Bragg grating, depends on the effective index of refraction of the core (n_{eff}) and the periodicity of the grating (Λ) through the relation

$$\lambda_B = 2neff \Lambda \tag{3}$$

For a temperature change of ΔT, the corresponding wavelength shift $\Delta\lambda_B$ is given by [29]

$$\Delta\lambda_B = 2\left(\Lambda\frac{\delta n}{\delta T} n\frac{\delta\Lambda}{\delta T}\right)\Delta T \tag{4}$$

The changes in the grating spacing and the index of refraction caused by thermal expansion result in a shift in the Bragg wavelength. This fractional wavelength shift for a temperature change ΔT may be written as [29]

$$\frac{\Delta\lambda_B}{\Delta T} = \lambda_B(\xi + \alpha) = \lambda_B K_T \tag{5}$$

where $\xi = (1/n) (\delta n/\delta T)$ is the fiber thermo-optic coefficient, which is equal to $8.6 \times 10^{-6}°C^{-1}$ for a germanium doped silica-core fiber and $\alpha = (1/\Lambda) (\delta\Lambda/\delta T)$ is the thermal expansion coefficient for the fiber ($0.55. 10^{-6}°C^{-1}$ for silica).

We note that for the case of a silica fiber, the wavelength–temperature sensitivities of 800 and 1.55 nm FBGs have been measured with values of 6.8 pm/°C and 13 pm/°C, respectively [30].

From Eq. (5), we can find that there exists a linear relationship between $\Delta\lambda_B$ and ΔT. Fig. 2 shows experimental results of a Bragg grating center wavelength shift as a function of temperature [29].
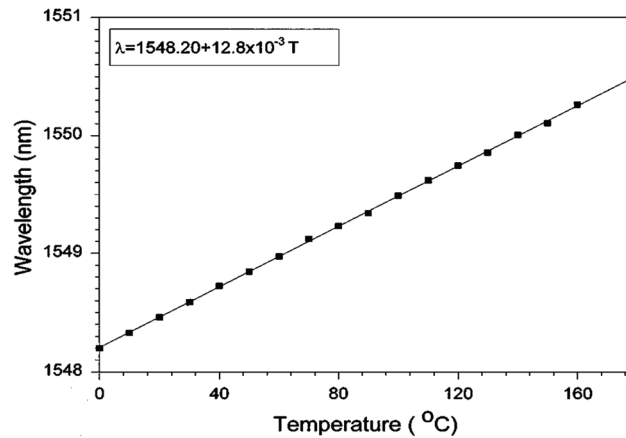
Figure 2: Bragg grating wavelength as a function of temperature change for a 1548.2 nm grating

2.3 Post-Mortem Dating Using Fiber Bragg Grating Sensors

The sensitivity of the FBG sensor to temperature results in a shift in Bragg's wavelength given by the following equation [29]:

$$\Delta\lambda = \lambda_B K_T \Delta T \tag{6}$$

Replacing the Eq. (1) in the Eq. (5) or

$$\Delta T = T_{\text{Rectal}} - T_{Ambient}$$

The time shifting of variation Bragg's wavelength become as the following equation:

$$\Delta\lambda = \lambda_B - \lambda$$

$$= \lambda_B.K_T.\left\{(37.2 - T_{Ambient}).\left(1.25e^{-kt}0.25e^{-5kt}\right)\right\} \tag{7}$$

3 Results and Discussions

3.1 Death-Time Profile

Usually, the human body always tries to keep its internal temperature at 37.2 degrees Celsius compared to ambient temperature. But when the person dies, the body loses this property and becomes inactive; it begins to be affected by the ambient temperature. Figs. 3–6 present various death-timeprofiles when Eq. (1) are simulated numerically by the Matlab software, and the result are verified by Henssge's nomogram for different ambient temperatures and for known body mass.

Table 1 summarizes the values of time of death (Tod) obtained of each profile of datation.

According to these figures, our results obtained by Matlab software are similar with those given by the Hengsse nomogram.

The Figs. 3b, 4b, 5b and 6b show 03 distinct phases: a phase called the initial thermal plateau (duration of 0.5 to 3 h) or during this period, the body temperature decreases very little. An intermediate phase of rapid semi-linear decay and a terminal phase of slow decay where the body temperature is eventually very gradually equalized with that of the surrounding environment

3.2 Evolution of Internal Temperature according Time Death for Different Ambient Temperatures

Figs. 7 and 8 show the datation profile *vs.* different ambient temperatures.

From Fig. 7, we can see that in the case when $T_{Ambient} < T_{Rectal}$, the internal temperature decreases until getting value of ambient temperature for all profiles.

In the case when $T_{Ambient} > T_{Rectal}$, the internal temperature increases until getting value of ambient temperature for all profile which is shown in Fig. 8.

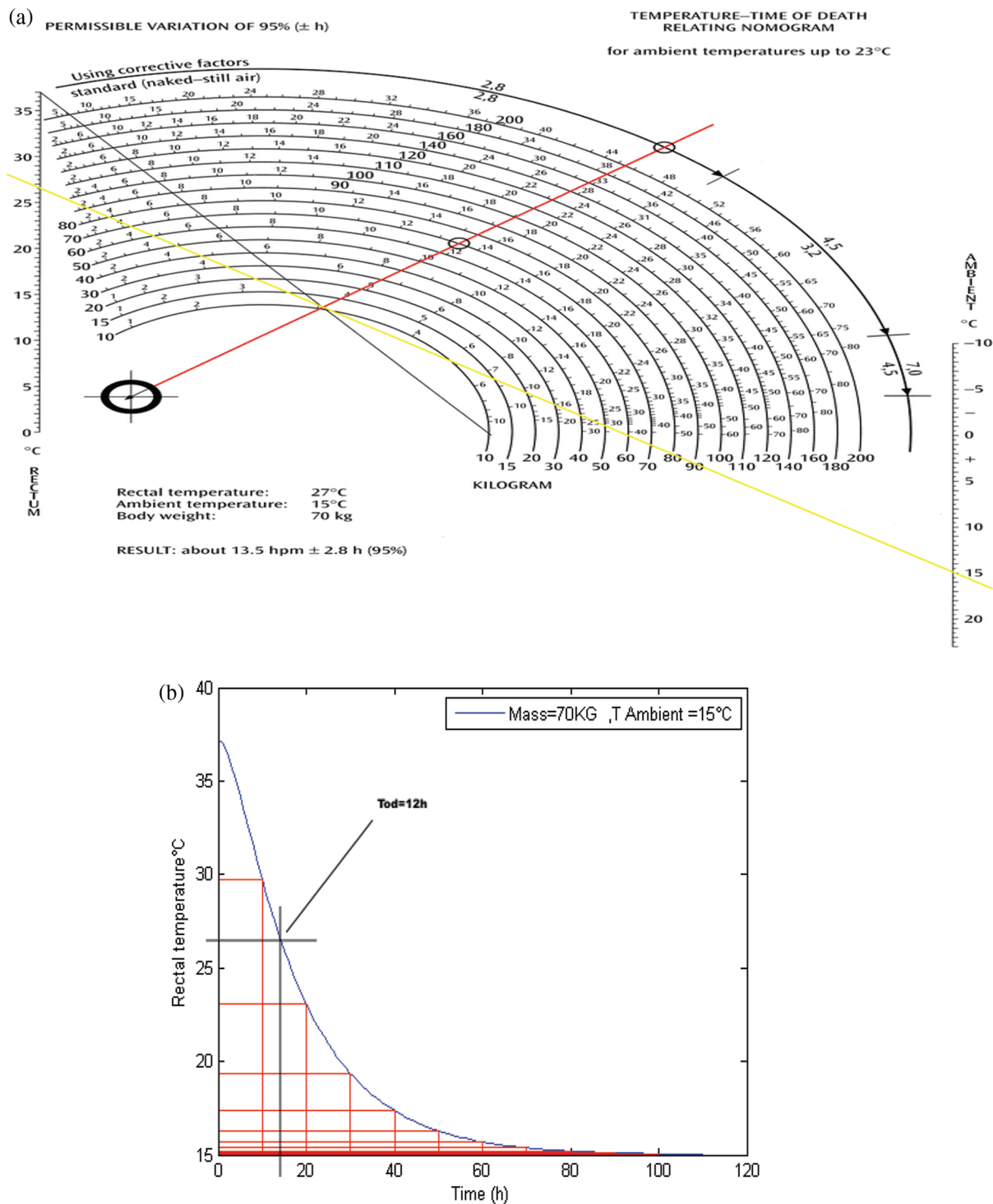### 3.3 Post-Mortem Dating Using FBG Temperature Sensors

Fig. 9 presents the time shifting of variation Bragg's wavelength given by Eq. (7).

We noticed that the profile curve of Fig. 9 is comparable to Henssge's equation given by Fig. 3 simulated by MATLAB.

Fig. 10 depicts the Bragg wavelength for different values of the body mass at the same ambient temperature.

From this figure, we can see that the heaviest body cools more slowly. Before arriving at a conclusion, let us analyze the results obtained using the FBG temperature sensors.
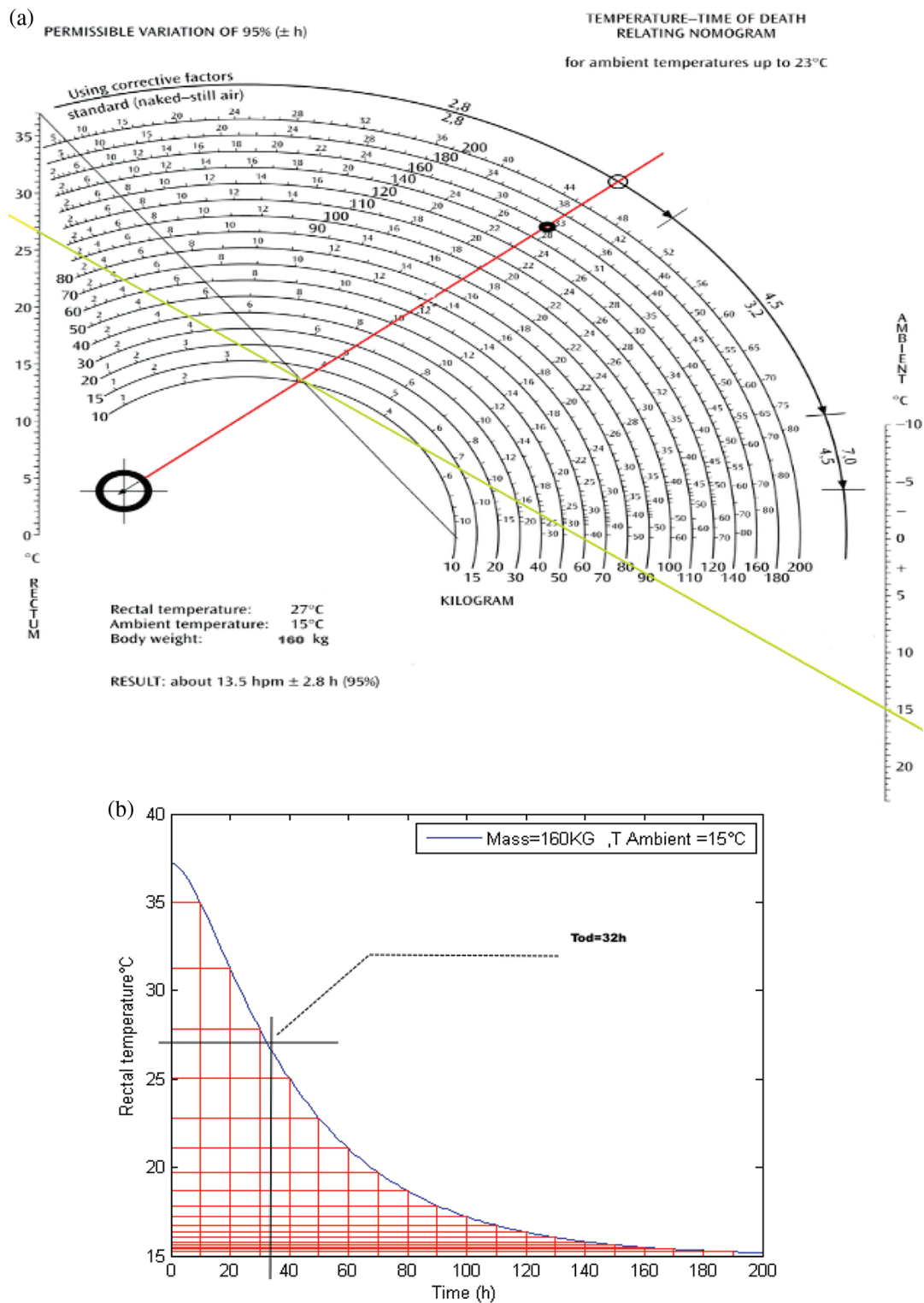
Fig. 11 presents a comparison between two dating methods, that are based on the use of the FBG temperature sensors and that related to the use of the simulated henssge's equation in the case of $T_{Ambient} > 37.2°C$. We clearly see that the two curves present the same profile and the result obtained by the two methods are comparable and presented in Table 2.

(a)

PERMISSIBLE VARIATION OF 95% (± h)

TEMPERATURE—TIME OF DEATH
RELATING NOMOGRAM

for ambient temperatures up to 23°C

Rectal temperature: 27°C
Ambient temperature: 15°C
Body weight: 70 kg

RESULT: about 13.5 hpm ± 2.8 h (95%)

(b)

Figure 3: Schematic presentation of death-time (a) By using Henssg's nomogram (b) Simulated datation

(a)

Rectal temperature: 28 °C
Ambient temperature: 18 °C
Body weight: 80 kg

RESULT: about 13.5 hpm ± 2.8 h (95%)

(b)
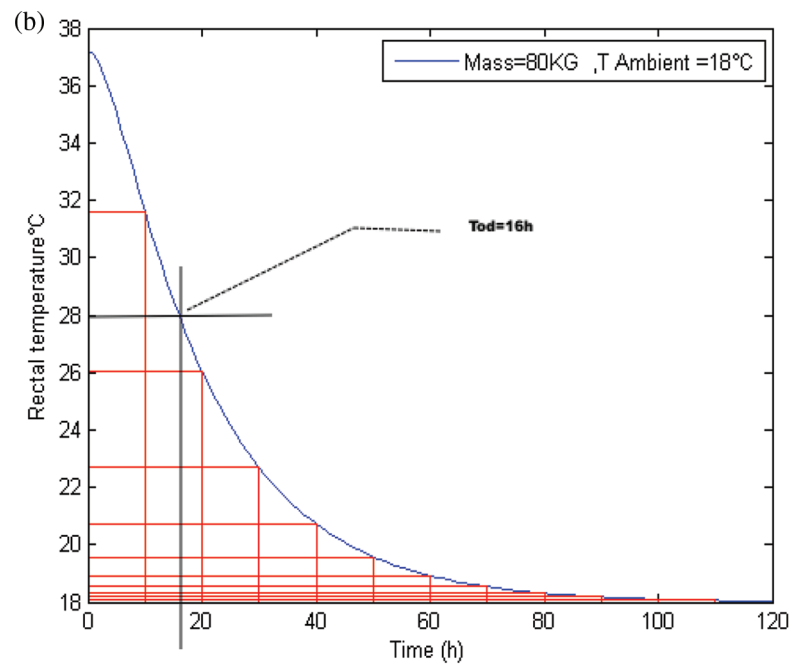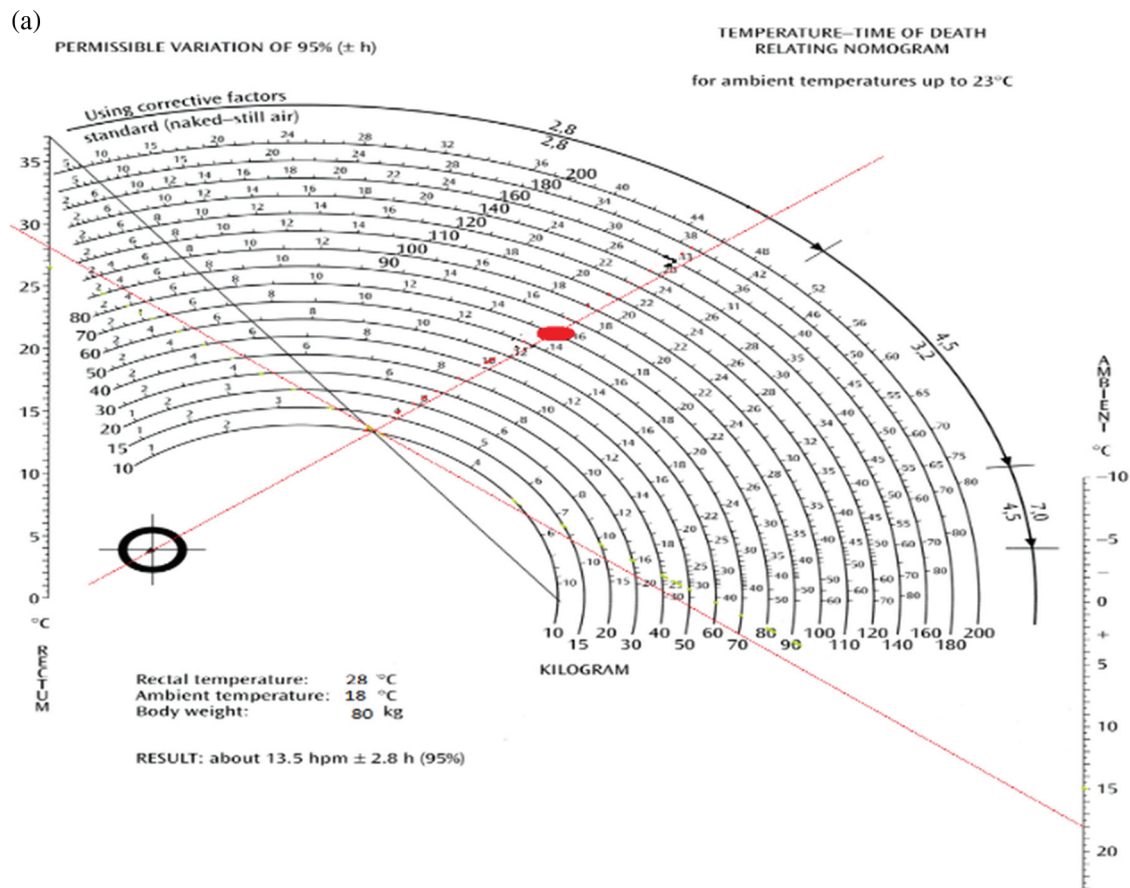
Figure 4: Schematic presentation of death-time (a) By using Henssg's nomogram (b) Simulated datation

(a) PERMISSIBLE VARIATION OF 95% (± h)

TEMPERATURE–TIME OF DEATH RELATING NOMOGRAM

for ambient temperatures up to 23°C

Rectal temperature: 27°C
Ambient temperature: 15°C
Body weight: 160 kg

RESULT: about 13.5 hpm ± 2.8 h (95%)

(b)

Figure 5: Schematic presentation of death-time (a) By using Henssg's nomogram (b) Simulated datation

According to the Figs. 11a and 11b and Table 2, we have found that are three cases:

Case 1: When the rectal temperature is 37.5°C and ambient temperature 40°C, the body warms up quickly so the time to death is 6 h.

Case 2: When the temperature of the rectum is 38.5°C therefore close to the ambient temperature 40°C, the body warms up slowly, which is the slow phase. In this phase, we find that the exact time of death is 18 h.

Case 3: When the body temperature is 39°C very close to the ambient temperature 40°C, a difference of 0.5 degree compared to the second case makes the difference of 8 h so we get 26 h.
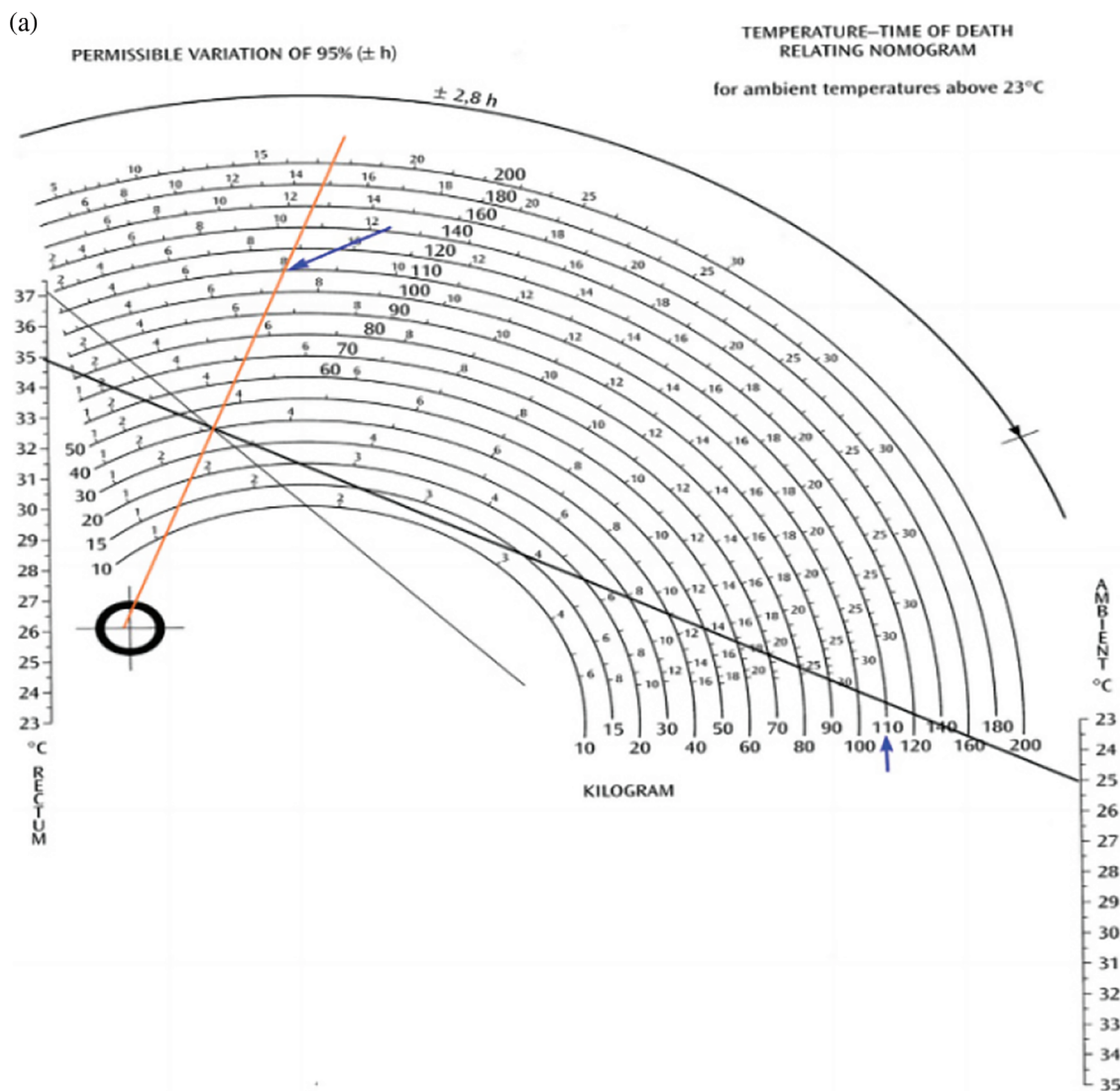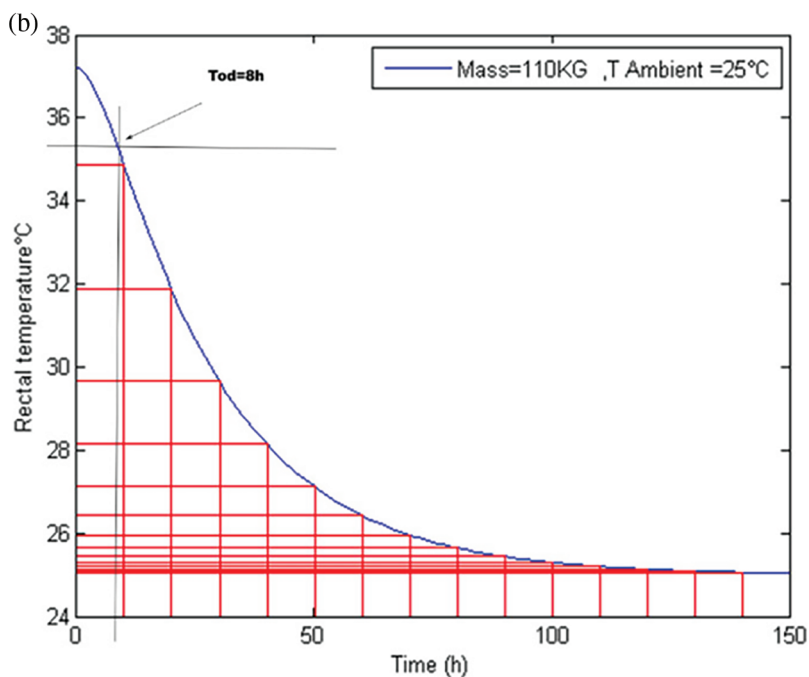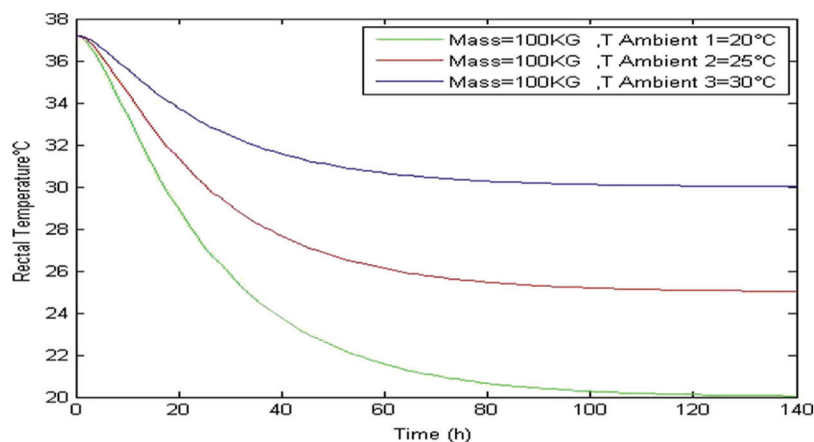

Figure 6: (Continued)

Figure 6: Schematic presentation of death-time (a) By Henssg's nomogram (b) Simulated datation

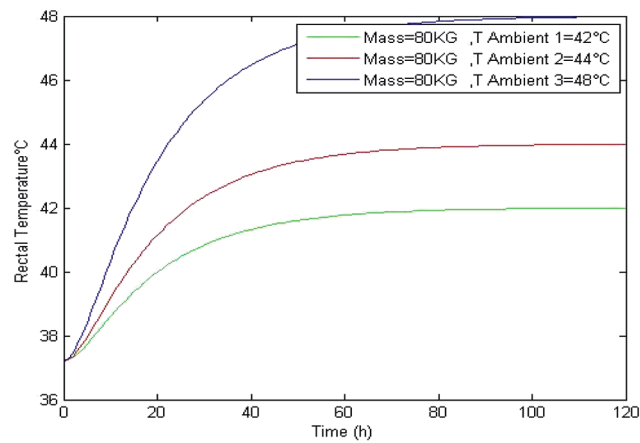**Table 1:** Comparison between Numerical and Henssge's nomogram results for time of death (Tod)

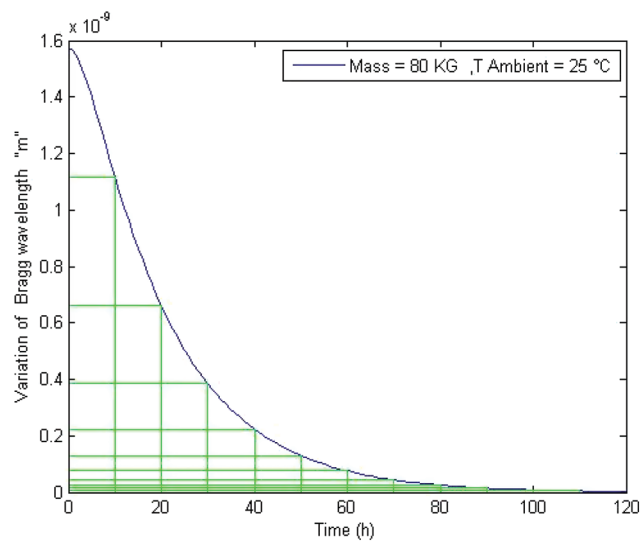|	Values used in our simulation		Time of death (Tod) results	
$T_{Ambient}$ °C	T_{Rectal} °C	Mass (kg)	Numerical result (Tod) (h)	Henssge's Nomogram result (Tod) (h)
15	27	70	12	12
18	28	80	16	16
15	27	160	32	32
25	35	110	8	8

Figure 7: Internal temperature *vs.* ambient temperature case of $T_{ambient} < 37.2$°C
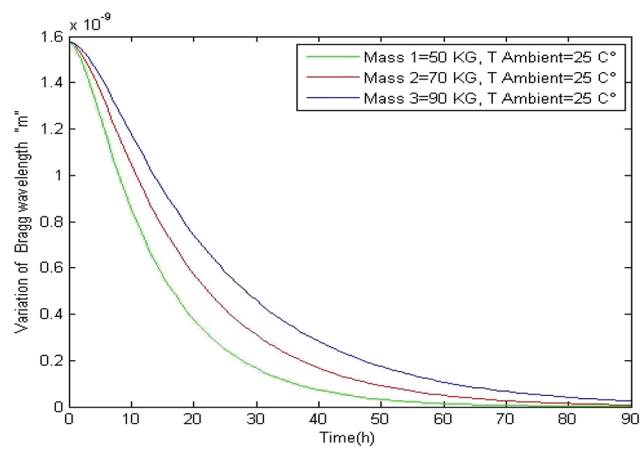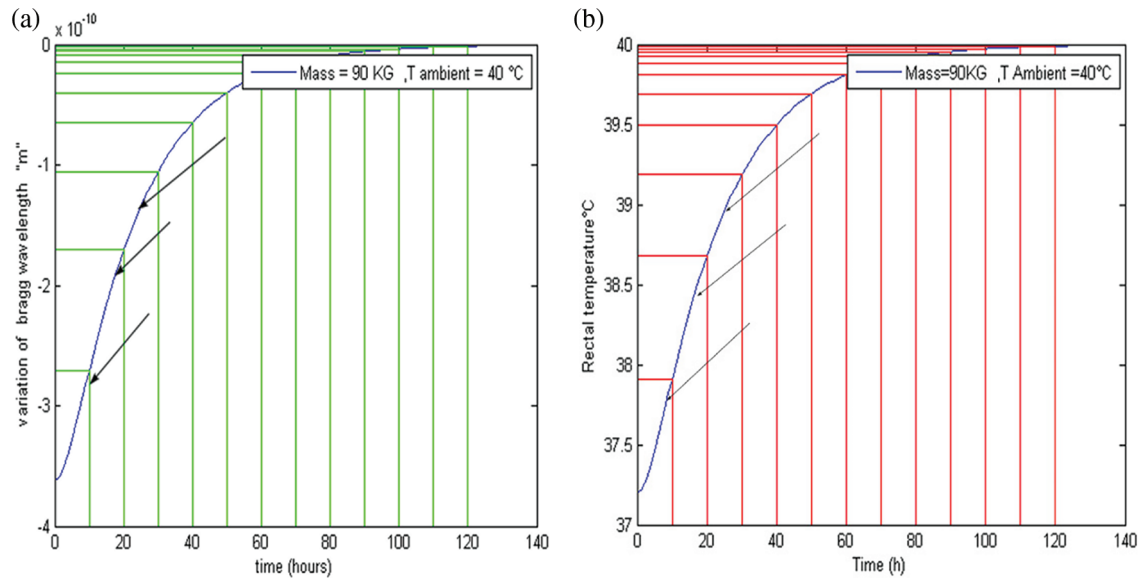
Figure 8: Internal temperature *vs.* ambient temperature case of $T_{Ambient} > 37.2°C$

Figure 9: Evolution of Bragg wavelength variation according to time

Figure 10: Evolution of Bragg wavelength variation according to time

Figure 11: (a) Dating using Fiber Bragg Grating temperature sensors (b) Dating using equation of Henssge

Table 2: FBG Temperature sensors results for time of death (Tod) and comparison

	Values used in our simulation				Time of death (Tod) results	
T_{Amb} °C	T_{Rectal} °C	Mass Kg	λ_B 10^{-9}m	$\Delta\lambda_B$ 10^{-10}m	FBG sensors (Tod) (h)	Henssge's equation (Tod) (h)
40	37.5	90	1550.13	−3.29	6	6
40	38.5	90	1550.13	−1.97	18	18
40	39	90	1550.13	−1.31	26	26

3 Conclusion

In conclusion, we have introduced a novel method for measuring the post-mortem interval (PMI) using Fiber Bragg grating temperature sensors. One should note that the Fiber Bragg Grating sensors have attracted considerable attention for measurement applications due to their greatly reduced size, low weight, flexibility, and immunity to electromagnetic interference in comparison with traditional sensing methods. The principal advantage of the Fiber Bragg Grating system chosen in this study is that the measured signal has the Bragg's wavelength. We note that modeling by using fiber Bragg grating sensors makes it possible to reproduce the thermal behavior of body. FBG sensors has shown its performance given the accuracy of results, which allows to be exploited for post-mortem dating at different ambient temperatures. One of the main advantages of this method is its use at high temperatures go up to 48°C (desert cases), which simulates the change in temperature of a body located outside. This work also provides a numerical simulation tool much easier to use than the use of field experiments on animal models, or human models. Finally, unlike other existing methods, it is simple to use and free to access, and does not require extremely detailed data to perform simulations. After comparison with the Henssged²nomogram, the predictions of this model have been used to test the validity of the Henssge nomogram in the case of a body subjected to high ambient temperature. The results indicate that the Henssge method cannot be used in the case of bodies found in an environment with high temperature. In view of these aspects of FBG sensing, it can be

predicted that this rapidly evolving technology can provide much better and effective solutions for various biomedical applications and be an integral part of the futuristic healthcare system.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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