Body temperature measurement from the 17th century to the present days

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Emma Angelini
Department of Applied Science and Technology
Politecnico di Torino
Torino, Italy
emma.angelini@polito.it

Sabrina Grassini
Department of Applied Science and Technology
Politecnico di Torino
Torino, Italy
sabrina.grassini@polito.it

Marco Parvis
Department of Electronics and Telecommunications
Politecnico di Torino
Torino, Italy
marco.parvis@polito.it

Luca Parvis
Department of Humanities
University of Oriental Piedmont
Vercelli, Italy
luca.parvis2@gmail.com

Andrea Gori
Educational Activities
Galileo Museum
Florence, Itraly
a.gori@museogalileo.it

***Abstract*—One of the first measurements in the health sector was probably the body temperature, whose increase, the so-called fever, was related to an illness condition. A fever develops as the body's natural way of reacting to and fighting infection. Attempts to standardized temperature measurements were developed in the 17^{th} century when physicians started to think of measuring this parameter and to develop new devices for assessing the body temperature. This scientific field has its origins in the works by Florentine scientists in the 1600s, meanwhile the development of today's thermometers and temperature scales began in the early 18th century. This paper describes an invention of the Grand Duke Ferdinand II de' Medici on display in the Galileo Museum in Florence, the clinical frog thermometer,tied to the wrist or the arm of the patient with the head of the frog facing upward. The performances of this device based on the Galilean thermometer principles, are compared with today's mercury and infrared thermometers.**

***Index Terms*—Fever, Body Temperature, Clinical Thermometer**

I. Introduction

The body temperature increases as the immunity system tries to fight an infection, so the body temperature was assumed since ancient times as an important parameter to understand the body response to an infection.

For this reason, the body temperature was one of the first clinical measurements at least when the thermometers began to appear on the market.

The body temperature is affected by several factors in addition to infections: measurement points in the body, actions such as eating, sport exercise, sleeping and finally circadian rhythm. Usually the body temperature reaches its maximum value around 6 pm and decreases to its minimum during the night at 3 am.

Table I shows the standard body temperature range.

TABLE I
Standard body temperature range

Grade	°C	F
Hypothermial	35 or low	95.0
Normal	36.5-37.5	97.7-99.5
Fever/Hyperthermia	37.5-38.30	99.5-100.9
Hyperpyrexia	40 or 41.5	104.0-106.7

Because the body temperature changes from point to point, physicians tried to find an easily accessible location, negligibly affected by any external condition. The temperature taken inside the mouth, the oral temperature, was selected, but other measurement points were chosen too, as in the rectum, the rectal temperature, and in the armpit, the axillary temperature. Between the different measurements points, variations of $0.3-0.5$ °C are detected. The ideal measurement position does not exist, however taking the oral temperature as a starting point, the rectal temperature is often lower of 0.2 °C and the axillary temperature is lower of about 0.4 °C.

Recently on the market several contactless thermometers may be found, designed to measure the temperature in the ear, the tympanic temperature, slightly different from either the oral and the rectal temperature.

There is an intrinsic not negligible uncertainty related to the way the temperature is measured, of 0.5 °C over a measuring range of $4-5$ °C. Moreover, the uncertainty of the measuring device has to be taken into account, in order to avoid considering misleading values.

Several types of clinical thermometers became available on the market since the seventeenth century with different performance and capabilities in an attempt to spread the idea of measuring the body temperature as a basic health indicator. Further on, some of them are presented trying to highlight the advantages and disadvantages of their employment.

II. The 'Frog' thermometer

The first attempts to measure the body temperature date back to the Galileo Galilei period, 16th-17th century, with the so called water thermoscope. A thermoscope is a device that shows changes in temperature. A typical design is a tube in which a liquid rises and falls as the temperature changes, there is not a unique correspondence with the temperature.

An Italian physician named Santorio Santorio, contemporary of Galileo, adapted the thermoscope to the clinical measurements obtaining a bulk model, which required considerable skill to be used and a long time to reach a stable measurement [3].

Later on Ferdinando II de' Medici, Grand Duke of Tuscany, who lived between 1610 and 1670 invented the so called "frog" thermometer,shown in Fig. 1.

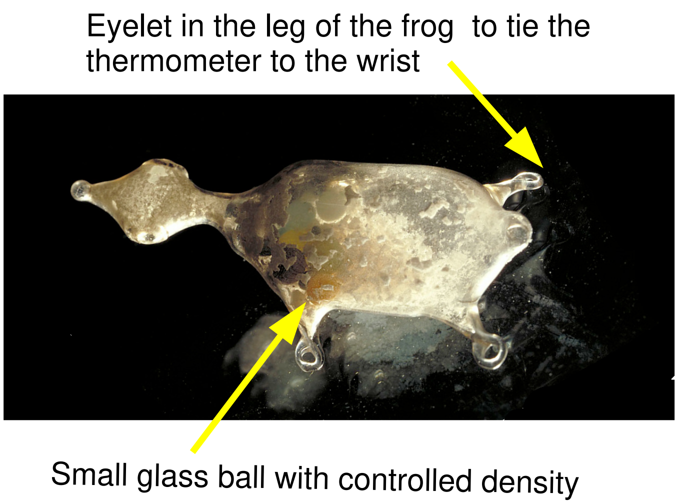

Fig. 1. The frog thermometer on display at the Galileo Museum of Florence.

The 'frog' thermometer or, as the Cimento academicians defined it, the botticino or small-toad thermometer, employs the Galileo idea of temperature measurement based on the variation of the density of a liquid. Some floating objects with a density close to the one of the liquid are put inside the container. When the temperature changes, the liquid density changes and, if the density of one object becomes lower than the liquid density, it tends to float moving upward. If the floating objects are tailored each one for a specific temperature with slightly different densities, the temperature can be inferred by looking at the higher density object which goes to the liquid surface for a specific environmental condition.

The frog thermometer is a small glass container, frog-shaped, which contains some small glass spheres of different density and is filled with acquarzente instead of water. The aquarzente chemical composition is uncertain, an ethanol rich mixture coming from distillation of grapes or more probably an inedible methanol rich mixture, the head of distillation. The device was intended to be used as a clinical thermometer and tied to a wrist or arm of the patient with the frog head facing upward.

The changes in body temperature, i.e. of the wrist, are transferred to the liquid inside the frog and produce movement of the glass balls, because of the decrease of the acquarzente density; when the density of a sphere becomes lower than the acquarzente density the sphere tends to move upwards, toward the frog head. Because of the spheres' sluggish motion, this thermometer was also called 'infingardo'or slothful.

The idea of replacing the water with the acquarzente, an ethanol or methanol rich mixture, may be attributed to the practical observation of the increase of sensitivity of the thermometer filled with acquarzente.

The density change of a liquid with temperature is a complex non-linear function. Several equations may be found in literature, as the DIPPR equation [4] that relies on four parameters which depend on the chemical compound:

$$\rho = \frac{A}{B^{\left(1+(1-\frac{T}{C})^{D}\right)}} \tag{1}$$

where ρ is the chemical compound density, T is the absolute temperature, and A, B, C, D are four constants which depend on the chemical compound.

Fig. 2 shows the normalized density variation of water and ethanol for the temperatures range of human body, from 35 °C to 42 °C. The density variation of methanol, not reported, is similar to the one of ethanol.

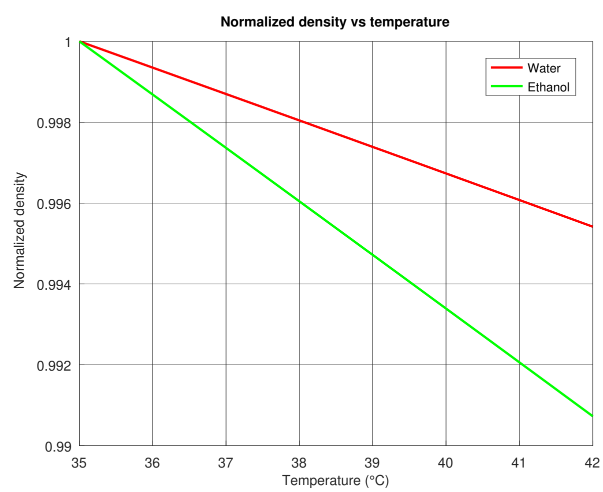

Fig. 2. Water and ethanol density variation with temperature.

In this temperature range both liquids change the density almost linearly, moreover the ethanol has a density variation about three times the one of water.

The glass container of the original frog thermometer shown in Fig. 1 lost the liquid, so a replica was realized, as shown in fig. 3.

The frog thermometer has a volume of about 24 cm^3. Each of the five glass spheres has a size of about 0.7 cm^3. Since the thermometer has to measure the temperature in the range of 36 °C to 42 °C the thermal resolution is of about 1 °C.

Defining the accuracy of this thermometer is not easy, because all the original devices are either broken or not acces-

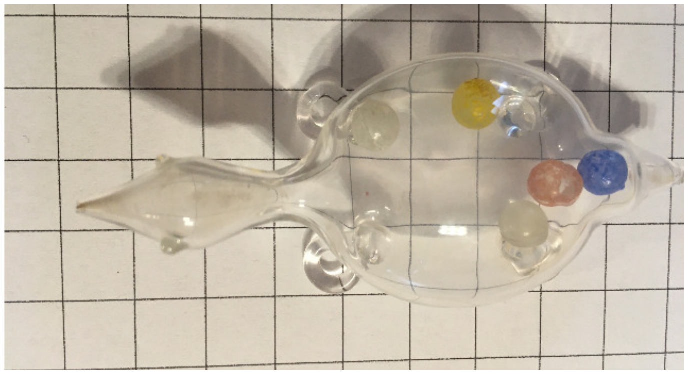

Fig. 3. Replica of the frog thermometer on display at the Galileo Museum. The replica contains five glass balls, the temperature resolution is about 1 °C.

sible, moreover the acquarzente composition is an undefined mixture of ethanol or methanol. However some interesting consideration can be drawn from the diagrams of fig. 2. In case of pure ethanol, the density variation with temperature can be approximated with a linear function, at least in the temperature range of interest:

$$\rho_{eth} = 773.84 - 1.025 \cdot (t - 32) \tag{2}$$

The linear equation approximates the density variation with temperature with a maximum error lower than 0.2% as shown in fig. 4.

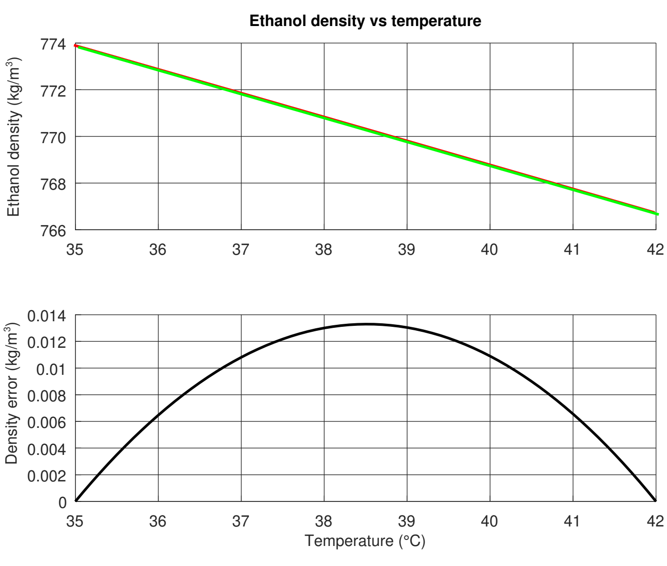

Fig. 4. Linear approximation of the ethanol density change with temperature. Up; in green the linear approximation, in red (barely visible behind the green line) the result from eqn. 1. Down: the difference.

The Galilean thermometers, extensively available on the market, have a dimension of 30 cm $\times$ 5 cm, with floating spheres 2 cm in diameter and a temperature resolution usually limited to $1 - 2$ °C. In order to float at a specific temperature, each sphere should weight about 3.2 g and the difference in weight between two spheres designed to float at a temperature difference of 2 °C should be of about 8.5 mg.

The dimensions of the frog thermometer are definitely smaller: the glass spheres have a volume of about 0.7 cm^3 and therefore the weight of a sphere immersed in ethanol has to be of 0.54 g, while, if the sphere should be in glass and solid, the weight should be only of 1.75 g.

In order to have spheres with different densities, able to float highlighting temperature differences of 1 °C, a possibility is to make hollow spheres and partially fill them with a liquid. If the wall of the sphere is one millimeter thick, the glass weight would be of about 0.17 g requiring an internal water content of 0.37 g, i.e. 0.37 cm^3.

The difference in weight of the water contained in a sphere floating at a specific temperature and in another floating at 1 °C higher would be of the order of 0.7 mg, a really small amount to be measured with the instrumentations available in the seventeenth century.

On the other hand, producing a lot of spheres and selecting them according to the temperature they float, would require the possibility to assess the temperature with an uncertainty lower than 1 °C, again a very difficult operation.

III. Mercury thermometer

One of the first and widely used clinical thermometer was the mercury thermometer. It belongs to the liquid-in-glass thermometers and was probably invented in the eighteenth century by Daniel Gabriel Fahrenheit in Amsterdam.

The glass mercury thermometer shown in Fig. 5 consists of a small bulb containing mercury which is attached to a thin glass tube whose internal volume is smaller than the volume of the bulb. Consequently any small change in the mercury density is reflected into a noticeable change in the length of the mercury column in the small tube. A tube constriction between the bulb and the tube is usually present so, once the mercury enters the tube due to its expansion, it does not return automatically to the bulb making the thermometer a maximum value thermometer. This is an important feature for a clinical thermometer, that once inserted either in the mouth, rectum or under the armpit, retains the maximum measured temperature, allowing the physician to read easily the value.

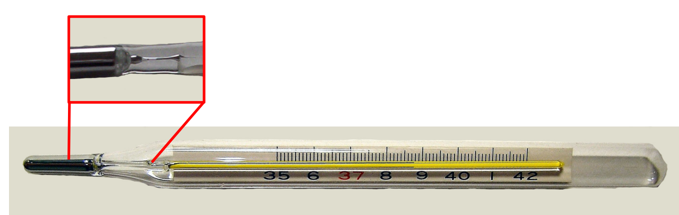

Fig. 5. A glass mercury thermometer with the tube constriction to keep the maximum value.

Several liquids, in addition to mercury may be used to build up a thermometer, as a matter of facts every liquid changes its density with temperature. The advantage of mercury is the high reflectivity and the easiness to read the column of mercury, the disadvantage its high toxicity especially in vapor form. A clinical thermometer contains about 0.4 g of mercury which, in case of breakage of the thermometer, can release toxic vapors.

From 2009 [1], the European Union approved a ban on non-electrical mercury thermometers and other mercury instruments for general sale to the public, therefore, the mercury thermometers were replaced by the gallium thermometers. They contain an eutectic alloy non-toxic and environmentally friendly whose chemical composition in weight% is 68.5 Ga, 21.5 In, 10.0 Sn; the alloy is slightly less reflective than mercury. As shown in Fig. 6, the gallium thermometer looks like a glass mercury thermometer, embeds the maximum constriction tube and has an accuracy comparable with the one of the mercury device.

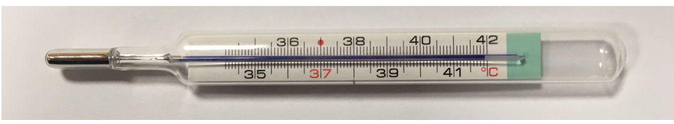

Fig. 6. A gallium thermometer, which replaced the glass mercury thermometers. The gallium bar read about 41.9 °C and has a silvering color.

Gallium and mercury thermometers are suitable for assessing the body temperature in the typical measuring points above cited (oral, rectum, armpit) and can be easily calibrated before entering the market, so their uncertainty can be of 0.1 °C or lower, making them suitable for acting as standard thermometers. Their main disadvantages are the relative slowness, several tens of seconds are needed to reach a stable reading, and the manual reset before each measure.

IV. Contact electronic thermometer

The contact electronic thermometers, shown in fig 7, having a shape similar to the mercury and gallium ones, can be used to assess the body temperature in the different points of the body, mouth, rectum and armpit.

They were introduced in the fifties as long as digital circuits and displays became extensively available. The contact electronic thermometer may employ several types of sensors, the most common are either NTC or digital temperature components. In both cases the sensitivity may be very high, better than 0.1 °C and the accuracy $\pm 01 - 0.2$ °C, however a periodical re-calibration is required. Due to the small dimensions of the sensitive tip, these thermometers can answer within seconds.

Fig. 7. A contact electronic thermometer, similar to the mercury thermometer.

After calibration and for the calibration period, their uncertainty is less than 0.1 °C and an audible alert sounds when the measurement is completed. As already observed, their main disadvantages are the relative slowness, several seconds, notwithstanding the smaller tip dimension with respect to gallium and mercury thermometers and the need of re-calibration.

V. Infrared Contactless thermometer

Contactless electronic thermometers rely on the infrared radiation emitted by the body. In principle they can react in less than one second so they can be considered instant thermometers, and they can measure the body temperature at any distance, provided that the air transparency to the infrared radiation in taken into account. Fig. 8 shows an example of this type of thermometer designed to measure both the temperature inside the ear and on the forehead by inserting and removing a specific tip cover.

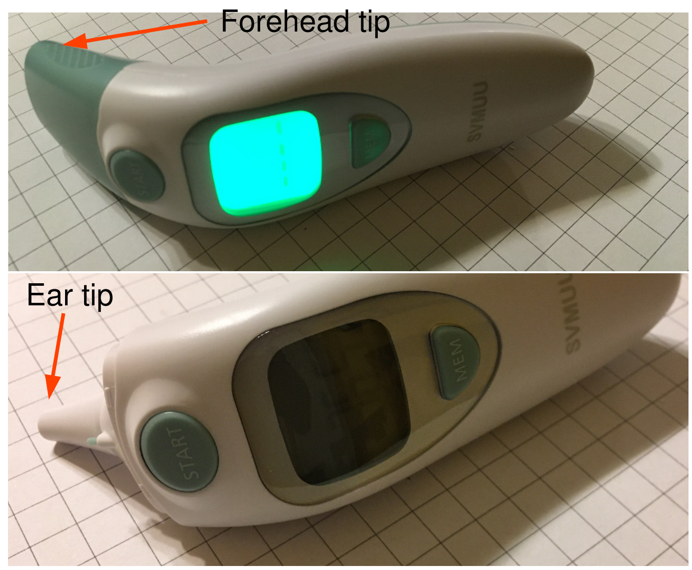

Fig. 8. An infrared contactless thermometer.

These contactless thermometers assess the temperature by measuring the environmental temperature and by using a specific sensor shown in fig. 9 sensitive to the infrared radiation emitted by the body.

One of the main problem of this type of thermometers is the body reflectivity which might alter the temperature reading. To avoid this problem usually an equivalent of the black hole is used to perform the measurement, by using the ear for the ear measurement and by going in contact with the forehead for the forehead measurement.

The infrared thermometers can provide a good accuracy in absence of ear infections, which might locally alter the local temperature and with the body in a rest condition and in equilibrium with the environment before any forehead measurement.

The thermometer shown in fig 8 has a resolution of 0.1 °C and claims an accuracy of ±0.3 °C in the case of tympanic

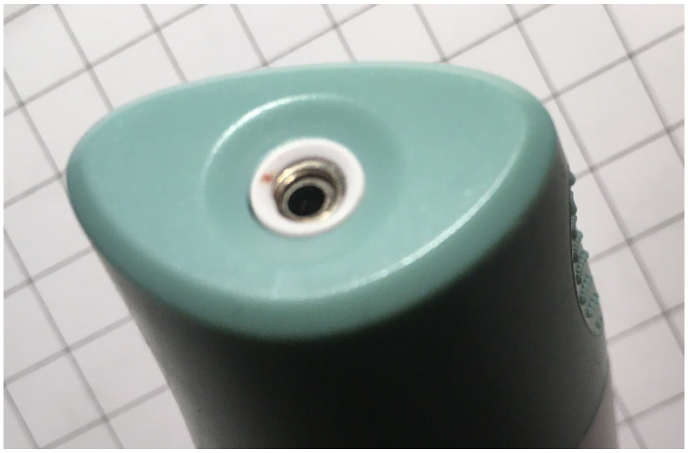

Fig. 9. The thermopile embedded into the infrared thermometer.

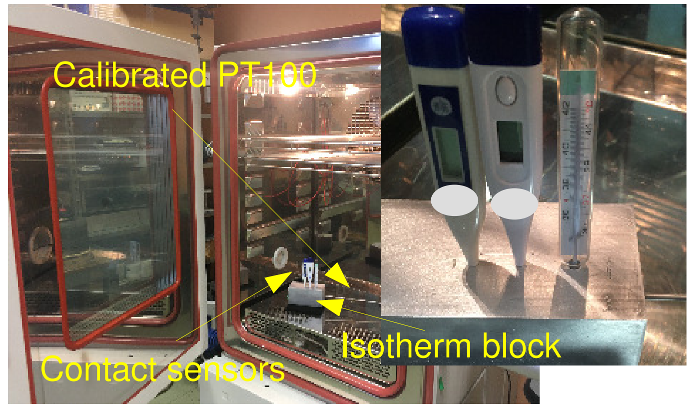

Fig. 10. The experimental setup used for the thermometers performances comparison.

temperature measurement and of ± 1 °C in the case of forehead measurement.

VI. Comparison of thermometers performances

The thermometers taken into considerations, with the exception of the frog one, not available, cost around 20$ and claim to be quite accurate.

Few studies deal with the comparison of different types of thermometers. In the paper [2] an investigation into the accuracy of different types of thermometers is presented. According to this study, the digital thermometers underestimate the body temperature of about 0.3 °C with respect to the glass mercury thermometer. The disposable thermometers have differences of more than 0.4 °C. The digital ear thermometer have about the same reading as the glass mercury ones.

Unfortunately, the contactless thermometer are designed to give the correct results only when measuring the body temperature of real patients and this require to perform the measurements in two steps: initially the comparison has been performed to assess the contact thermometer accuracy without taking the measurement point into account, then tests have been performed to check the thermometers on real patients.

A. *Climatic chamber tests*

The authors arranged the setup shown in fig. 10 in order to assess the contact thermometer accuracy, regardless of the intrinsic body temperature uncertainty due to the measurement position.

To this aim, an isotherm block has been realized with an aluminum block which allows to obtain a uniform temperature. The isotherm block has holes designed for the insertion of the contact thermometer tips and of a Calibrated Platinum resistor for evaluating the actual temperature.

The actual temperature has been estimated by measuring the PT100 resistance using an HP3458 DMM in 4-wire mode and by using the Calendar-Van Dusen equation:

$$R = R_0 \left(1 + AT + BT^2\right) \tag{3}$$

where $R_0 \approx 100\ \Omega$, $A \approx 3.9 \cdot 10^{-3}\ °\text{C}^{-1}$, $B \approx -5 \cdot 10^{-7}\ °\text{C}^{-2}$ are the coefficients obtained during the PT100 calibration.

According to the calibration certificate, the difference in temperature is lower than 0.01 °C, meanwhile the extended ($K = 2$) standard accuracy is $U_s = 0.05$ °C. By using the setup of Fig. 10, the extended temperature uncertainty in the range $35 - 42$ °C can be estimated to be below $U_t = 0.1$ °C.

All tests have been performed on three devices: a gallium thermometer, a brand new electronic contact thermometer and a five years old electronic thermometer.

The tests have been performed in a climatic chamber in a temperature range of 36 °C to 42 °C. The results of the thermometers performances are shown in fig. 11.

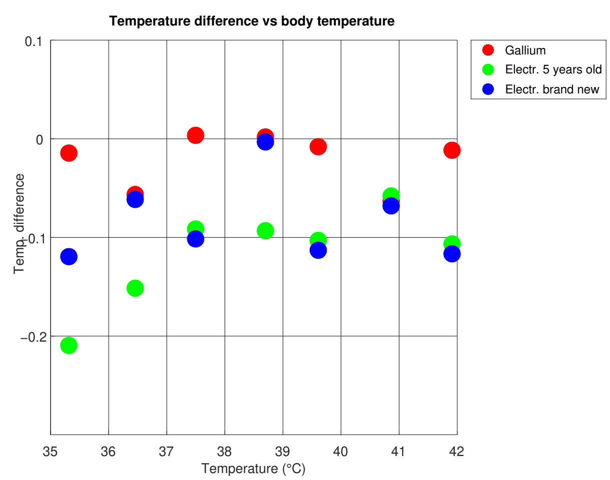

Fig. 11. Results of the tests carried out in a climatic chamber for evaluating the performances of the thermometers.

The three thermometers measure a temperature close to the actual one with a maximum deviation of the order of 0.2 °C, i.e. close to the thermometer resolution and of the order of the extended standard uncertainty of the calibrated reference thermometer. The electronic thermometers tend to underestimate the body temperature of a value of the order of the thermometer resolution. The 5 year old thermometer behaves quite well also without recalibration: only for low temperatures, i.e. below $37\ ^{\circ}C$ the temperature difference exceeds $0.1\ ^{\circ}C$.

B. In-vivo tests

In-vivo tests have been performed measuring, with the thermometers listed below, the body temperature on six volunteers, four males and two females in normal health conditions:

- A gallium thermometer and a contact electronic thermometer for measuring the oral temperature
- A contactless thermometer for measuring the tympanic temperature and the temperature on the forehead.

The tests have been carried out to evaluate the influence of the different measuring points on the temperature value. The thermometers have been used according to the manufacturer specifications: the gallium thermometer response has been read after 5 min from the contact, the contact electronic thermometer and the contactless thermometer have been read after the audible beep at the end of the measurement.

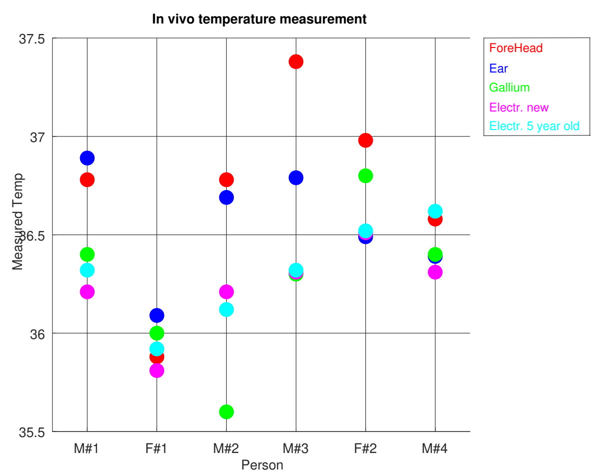

Fig. 12. Results of the comparison of the thermometers performances in the in-vivo test.

Fig. 12 shows the results of the in-vivo tests: the variability is higher than in the climatic chamber tests and is of the order of $1\ ^{\circ}C$ for each person. Moreover, considering the same measurement point, as in the case of the contact thermometers, a difference of $0.2-0.5\ ^{\circ}C$ is often observed. The contactless thermometer had a reading generally higher than the other thermometers with a maximum difference of $0.5\ ^{\circ}C$. This difference may be attributed to some intrinsic corrections inside the contactless thermometer, which otherwise should measure a lower temperature value.

VII. Conclusions

Since the 17^{th} century, the body temperature was recognized as an important measurement in the health sector. As a matter of facts, the body temperature is a meaningful prognostic measurement any physician may carry on easily on patient's body with clinical thermometers that allow to perform the measure with a small uncertainty. During centuries scientists tried to make clinical thermometers with tailored performances in order to overcome the problems related to size, slowness, and uncertainty of the measurement itself. Attention has been paid in this paper to the description of the historical frog thermometer, attributed to Grand Duke Ferdinand II de' Medici. The intrinsic uncertainty of the body temperature can be of more than one degree Celsius, however if one body location is selected and the normal temperature of a specific patient, such an intrinsic uncertainty decreases, no more than $0.3\ ^{\circ}C$ making the body temperature measurement an important clinical indicator.

Comparative tests performed on different types of clinical thermometers revealed differences, with respect to a reference thermometer up to $0.1\ ^{\circ}C$. This low value does not hold for practical measurements where differences of up to $0.7\ ^{\circ}C$ can be expected. Once the measuring device has been fixed, the repeatability is of the order of $0.2\ ^{\circ}C$, a value that for a specific patient is suitable to detect any change in the body temperature and to become an important prognostic measurement.

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