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Comparison of the temperature accuracy between smart phone based and high-end thermal cameras using a temperature gradient phantom

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ABSTRACT

Recently, low cost smart phone based thermal cameras are being considered to be used in a clinical setting for monitoring physiological temperature responses such as: body temperature change, local inflammations, perfusion changes or (burn) wound healing. These thermal cameras contain uncooled micro-bolometers with an internal calibration check and have a temperature resolution of 0.1 degree. For clinical applications a fast quality measurement before use is required (absolute temperature check) and quality control (stability, repeatability, absolute temperature, absolute temperature differences) should be performed regularly. Therefore, a calibrated temperature phantom has been developed based on thermistor heating on both ends of a black coated metal strip to create a controllable temperature gradient from room temperature 26 ºC up to 100 ºC. The absolute temperatures on the strip are determined with software controlled 5 PT-1000 sensors using lookup tables. In this study 3 FLIR-ONE cameras and one high end camera were checked with this temperature phantom. The results show a relative good agreement between both low-cost and high-end camera’s and the phantom temperature gradient, with temperature differences of 1 degree up to 6 degrees between the camera’s and the phantom. The measurements were repeated as to absolute temperature and temperature stability over the sensor area. Both low-cost and high-end thermal cameras measured relative temperature changes with high accuracy and absolute temperatures with constant deviations. Low-cost smart phone based thermal cameras can be a good alternative to high-end thermal cameras for routine clinical measurements, appropriate to the research question, providing regular calibration checks for quality control.

Keywords: Thermal camera, phantom, quality, smart phone.

1. INTRODUCTION

With thermal cameras the spatial and temporal variations in temperature can be measured and presented as an image. The last years the use of thermography has enormously increased[1,2] and we expect that this will continue in the future. With the development of micro-bolometer array’s without cooling low cost thermal camera’s with a good temperature and spatial resolution became available. This has contributed to an increase in use of thermal cameras in clinical applications. Depending on the research question absolute temperatures or absolute temperature differences or qualitative temperature differences can be measured. For the first two possibilities we need calibrated camera’s if only differentiations in heat spots need to be observed then calibration is not that important.

Thermography is based on the fact that all materials above absolute zero (-273.15 C) emit electromagnetic radiation which is proportional to its temperature[3,4]. The spectral properties of this radiation are described by the radiation law of Planck. The energy per second radiated from a body depends on the surface area and the temperature described by the Boltzmann equation:

\[ P = \varepsilon \sigma A T^4 \]  

\[ T = T \text{ in } [K] \]

\[ \sigma = \text{Stefan Boltzmann constant} = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \]

\[ \varepsilon = \text{emissivity} \]

\[ A = \text{surface area of body} \]
The thermal camera collects all the infrared light in the wavelength band of 8-12 µm (Long Wave Infra-Red, LWIR) received from the surface of an object and relates this to a temperature.

The surface properties of the object influences the total infrared energy leaving the object. This can be the emitted radiation based on the objects temperature, the transmitted light through the object and the reflected light from the surface (Kirchhoff’s Law):

\[ \varepsilon + \rho + \tau = 1 \]  
(2)

\( \varepsilon \) = emissivity  
\( \rho \) = reflectivity  
\( \tau \) = transmissivity

The camera sees the total radiation and cannot distinguish between the sources, the operator must give the camera the coefficients of each source to calculate the correct temperature. Metals and tissue are opaque, then only the emissivity and reflectivity at the infrared region influence the temperature measurement. The atmosphere between the object and the camera will also emit and absorb radiation in the IR band depending on the temperature and its composition. The emissivity is a measure of efficiency of a surface to emit radiation relative to a blackbody. A blackbody is theoretically a perfect absorber (all incoming radiation is absorbed) and there is no reflection or transmission, the absorption is equal to the emissivity and is equal to 1.0. All real surfaces have an emissivity lower than 1.0. Emissivity depends on the material, the roughness of surface (polished or rough), wavelength (MWIR or LWIR range), temperature of material, viewing angle and surface geometry and should be written as: \( \varepsilon(\lambda,T,\Phi) \). The emissivity of a black paint or chalkboard paint (CBP) is very high (\( \varepsilon_{black\ paint} = 0.9\text{-}0.94 \), \( \varepsilon_{CBP} = 0.98 \)) comparable to human skin (\( \varepsilon_{human\ skin} = 0.98 \) race and skin color has no influence). If no emissivity correction is done the observed object temperature is colder than its real temperature.

The resolution of the camera and the spot size of the object in pixels can influence the accuracy of the measurement. Nearby surfaces with deviating temperatures can influence the actual temperature. The spot-size must be at least 10 pixels in diameter for a meaning full temperature measurement and 20 pixels in diameter to give an accurate measurement.

In addition to the correct use of thermography it is necessary to know your thermal camera; how accurate is the absolute temperature measurement, how constant is the temperature registration over time (no temperature drift), how reproducible is the temperature measurement, how accurate is the relative temperature difference (between different areas in the image or at one location at different time stamps) or how correct is the temperature measurement at different distances. This we compare for one high end camera and 3 low-end smartphone based camera’s.

2. METHOD AND EXPERIMENTAL SETUP

2.1 Method

The standard calibration tools for IR thermometers and thermal cameras are blackbody reference sources [5], the uncertainty of these blackbody sources is around 0.2 C, the measurements and equipment are in conformity with the standard ISO/IEC 17025:2005. In this study we are not calibrating the camera’s, this study compares the performance of the camera systems using a temperature-gradient tool. It is a practical tool to test the camera’s on performance of absolute temperature absolute temperature differences (gradients), repeatability and stability. These test can be performed on a regular basis to find out if there are possible system errors or calibration errors. If a discrepancy is found between the camera and the gradient tool then the camera can be tested with qualified calibration tool. The idea of this gradient temperature tool is an easy to use testing tool for a quality control of the thermal camera in daily practice.

2.2 Materials

Thermal Camera: FLIR- ONE

The low-end camera in this test is the FLIR-ONE (FLIR systems, Wilsonville, OR, USA), it is a smart phone add-on, in this study the camera is attached to an iPad (Apple, Cupertino, CA, USA). The FLIR ONE contains two cameras, a thermal camera (160x120 pixels) and a visible VGA camera (640x480 pixels) and has a temperature range of -20° to
120° C with a temperature resolution of 0.1°C. The camera is connected to an external battery using a mini USB connector for long-term measurements. The acquisition and analyzes software applied is Vernier Thermal Analysis (Vernier Software & Technology, Beaverton, OR, USA).

**Thermal Camera: Xenics Goby 384**

The high-end thermal camera was a calibrated (2016) Xenics Gobi 384 (Leuven, Belgium), with an uncooled microbolometer and a 384x288 pixel array. The lens was an OPHIR SupIR 18mm. The sensor has 16 bit dynamic range and a spectral sensitivity LWIR (8 to 14 μm). The data were recorded and analyzed with Xeneth64 (Xenics, Belgium) software, the camera has an ethernet interface to a laptop PC, the data were acquired with 25 Hz.

![FLIR ONE and Xenics Goby 384](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

*Figure 1 Left the FLIR ONE thermal camera and on the right the Xenics Goby 384 thermal camera.*

The temperature gradient phantom is made of two heater-blocks with thermistor temperature feedback controlled system with an accuracy is 0.2 °C (figure 2 and 3). The temperature can be set from 26 °C to 100 °C. The metal strip is made of aluminum and is back-coated with blackboard chalk paint with an emissivity of 0.98. On this strip five Pt1000 are connected with a measuring error is 0.2 °C. Temperature stabilization is done by measuring and controlling. A feedback system minimizes the difference between the measured temperature and the set value. A proportional–integral–derivative (PID) controller algorithm calculates a correction value, by which the heating is adjusted. We estimate because of resistance transitions between the electronic parts that the accuracy of the total system will be 0.5 °C.

The standard calibration of the thermal camera is performed using calibrated radiation sources, these can produce the desired temperatures with a high stability. The temperatures are measured with a high precision calibrated thermometer, the emissivity is known under these conditions the calibration constants for the infrared sensors can be determined.

The gradient system is not intended to do a calibration of the IR thermal camera but it produces constant temperatures or constant temperature-gradients.

The gradient system produces constant temperatures or gradients over the length of the black metal strip. Because the gradient system has no active cooling the temperature could not be kept constant over longer time periods at high temperature settings. For these high settings active cooling was applied with a fan this gave stable temperature gradient over longer times.

In this study temperature gradients were applied in physiologically possible temperature changes, we applied a gradient of 10 °C at different starting temperatures.
2.3 Measurements and setup

A comparison is made between the high-end and low-end IR thermal camera on the following topics:

- Uniformity of the sensor
- Repeated measurements, the camera is switched off for 1 minute between the different measurements.
- Absolute temperature
- Absolute temperature difference
- Temperature relation to distance (Object distance)
- Temperature gradient, two gradients over 10°C from 30 °C -40 °C and from 40 °C -50 °C

The measurements setup are shown in figure 4 and 5, the whole system is placed in a room with no other heating sources and placed in a shielded environment to prevent reflections from other sources.
3. RESULTS

3.1 Uniformity over sensor

The uniformity of the sensor is measured imaging a flat black coated metal plate (emissivity in the camera is set to 1.0), at constant room temperature (setup figure 4). The cameras are placed at a distance $D = 30$ cm and the black metal plate has a temperature of $22.2 \pm 0.5$ °C.

The field of view (FOV) of the cameras see only the black metal plate, an example of the temperature image of both cameras is shown in figure 6.

![Sensor images](image)

*Figure 6: On top is an image of the sensor with a temperature range of 2 °C. The temperature variation over the diagonal (B) is shown below and the average over the whole screen is calculated in area A. The high end camera is on the left and the low end camera on the right site of the figure.*

Analyses are performed in 2 ROI’s: (A) a square area over the whole sensor and (B) over the diagonal of the sensor. The average over the whole sensor (ROI A) in one image is for the high-end camera $23.2 \pm 0.3$ °C and for the low-end camera $23.8 \pm 0.3$ °C. In one image a variation over the diagonal B is for the high-end camera $1.1$ °C and for the low-end $0.4$ °C. A measure for the stability over time (minutes) is the standard deviation in the average in area A; for the high-end camera is this $0.2$ °C and for the low-end camera ~ $0.6$ °C.

3.2 Repeatability

The repeated temperature measurements are preformed using the setup of figure 4, the distance is $D=30$ cm. Between all the measurements the equipment is switched of for at least 1 minute.
We observe that the first measurement deviate much for the later ones this can be induced to start-up effects of the cameras. If we leave the first measurements out we find still that all cameras have a deviation from the real temperature but measure at a constant temperature level. The standard deviation of the variation in apparent temperature (without start-up effect) is for the high-end Xenics camera 0.7 °C and for the low-end FLIR-ONE cameras respectively ±0.13, 0.35 and 0.35 °C. The temporal variation in temperature within each measurement is small: 0.05 – 0.1 °C.

3.3 Temperature gradient measurements

The experimental setup is according to figure 5, the object distance D= 30 cm. The temperature over the gradient phantom is set in the physiological temperature range of 30-40 °C and at a higher temperature range 40-50 °C. The temperatures are measured with 5 Pt1000 sensors of the phantom and at 3 ROI on the strip with the thermal cameras at position 1, 3 and 5 in figure 8.

The results are presented in figure 8, the real (phantom temperature measurements) and the apparent temperatures (thermal cameras) are fitted with a 2e order polynomial function. The Xenics camera shows parallel curves for the real and apparent temperatures. The apparent temperature is 3 degrees Celsius lower for the 30-40 °C gradient and 1 degree Celsius lower for the 40-50 °C gradient. The three FLIR-ONE camera’s differ from each other, 2 give lower and 1 gives a higher apparent temperature. The apparent and real temperature curves are not parallel over both the temperature gradients.

The set absolute temperature differences over the metal strip of the phantom is 10 ± 0.5 °C (figure 9). The Xenics camera measures a temperature deference within the accuracy of the phantom, a deviation smaller than 5%. The FLIR ONE cameras have a larger deviation of 14, 12 and 5 %.
Figure 8 The apparent temperatures measured with the four thermal cameras (solid lines) and the real temperatures measured with the Pt1000 on the gradient phantom (dotted lines). All curves are fitted with 2e order polynomial function.

Figure 9 The absolute temperature differences between point 1 and 5 are presented for the four cameras and for the repeated measurements. The error bars give the standard deviation within each measurement.
3.4 Temperature measurement in relation to the object distance

We use the experimental setup of figure 5, the temperature of the metal strip is set to a constant level of $26 \pm 0.5 \degree C$ and the distance D is varied from 10 to 200 cm. The object is always put in focus of the Xenics camera, for the FLIR-ONE camera’s both cameras are aligned at each object distance.

![Temperature vs object distances](image)

*Figure 10 The apparent temperature from the four thermal cameras as function of the object distance. The phantom temperature is constant and $26 \pm 0.5 \degree C$.*

The Xenics camera gives over the object distance range of $20 – 150 \text{ cm}$ the correct temperature within the accuracy of the phantom.

The FLIR-ONE 1 and 2 camera give within the accuracy range of the phantom ($\pm 0.5 \degree C$) constant results in the measurement range of $10 \text{ cm} – 150 \text{ cm}$, the absolute temperature is shifted for camera 1. For camera 2 the absolute value is in accordance with the phantom. The FLIR-ONE -3 gives a large spreading in temperature.

4. DISCUSSION

In clinical thermal imaging mostly absolute temperature differences are measured. This can be done over a time period, the measurements are performed in one ROI on the sensor. This requires stable cameras, as we have seen in the measurements both camera are stable over a time period ($0.2 \degree C$ for the high end and $0.6 \degree C$ for the low-end camera). Or this can be done within one image, between different areas of the sensor. Now the uniformity of the sensor is important. This study shows that the temperature sensitivity at different regions can differ more than 1 degree Celsius for the high-end camera and $0.4 \degree C$ for the low-end camera.

The absolute temperatures of the gradient phantom system was verified with external thermocouples and a calibrated pyrometer. The constancy and homogeneity of the black coated metal plate (figure 4) can be questioned. We assume that the plate after a long time ($\geq 24 \text{ hours}$) was at room temperature. This is most likely the case because the room temperature is constant throughout the measurement, and there were no heat sources close to the black plate. This is also confirmed when the plate is slightly moved (left-right), we observed that the temperature images of figure 6 did not change.

The FLIR-ONE camera can measure correct temperature differences as they are small ($\leq 5 \degree C$) in chapter 3.3, the camera may not be switched off between measurements over time (chapter 3.2). If temperatures within one image are compared the FLIR-ONE is as accurate as the high-end camera. This is of importance in studies were e.g. temperature differences between healthy and diseased tissue are compared[6].

Repeated absolute measurements (chapter 3.3) show offsets in temperature. This is important when studying absolute temperature comparisons over short time periods, the cameras may not be switched off.
To know your own camera the measurements in chapter 3 should be performed. The three FLIR-ONE cameras give different results and camera number-3 gives large deviations, this camera was one of the first of this generation and can possibly differ in hard and software. All the four cameras give small variations in temperature over time, the test measurements were done for only several minutes. In future studies the stability should be checked over longer time periods. The analyzing software for the high-end Xenics camera is much more sophisticated than the Apps of the FLIR-ONE camera. This limitation may hinder the deployment of these low-end cameras. The temperature – object distance variation show that for clinical relevant distance ranges (20-150 cm) the Xenics and 2 FLIR-ONE cameras give good results.

5. CONCLUSION

A summary of the findings in this study are shown in the table below.

<table>
<thead>
<tr>
<th></th>
<th>High End Xenics Gobi 384</th>
<th>Low –End FLIR-ONE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup system</td>
<td>- Connection laptop</td>
<td>+ tablet of iPhone</td>
</tr>
<tr>
<td>Analyzing software</td>
<td>+ more sophisticated</td>
<td>- Limited tools</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>+ 384x288</td>
<td>- 160x120</td>
</tr>
<tr>
<td>Spatial temperature variation over sensor</td>
<td>- Vary up to 1.0 ºC</td>
<td>+ Vary up to 0.4 ºC</td>
</tr>
<tr>
<td>Temporal variation within one measurement</td>
<td>+ whole sensor 0.2 ºC</td>
<td>- Whole sensor ~ 0.6 ºC</td>
</tr>
<tr>
<td></td>
<td>+ ROI temporal stdv 0.05-0.1 ºC</td>
<td>+ ROI temporal stdv ~ 0.2 ºC</td>
</tr>
<tr>
<td>Absolute temperature</td>
<td>+ constant deviation</td>
<td>- Constant deviation</td>
</tr>
<tr>
<td></td>
<td>+ up to 1 ºC deviation</td>
<td>- Up to deviation 3 ºC</td>
</tr>
<tr>
<td>Repeated measurements</td>
<td>+ vary &lt; 0.7 ºC</td>
<td>+ vary &lt; 0.35 ºC</td>
</tr>
<tr>
<td>Gradient step 10 ºC</td>
<td>+ constant deviation from real temperature</td>
<td>- Variation in deviation from real temperature</td>
</tr>
<tr>
<td>∆ Absolute temperature</td>
<td>+ small &lt; 0.5 ºC (&lt; 5%)</td>
<td>- &lt; 14, 12 and 5% deviation of real T</td>
</tr>
<tr>
<td></td>
<td>(within variation of phantom)</td>
<td>( for real step T = 10 ºC)</td>
</tr>
<tr>
<td>Object distance</td>
<td>+ 20 - 150 cm &lt; 0.5 ºC</td>
<td>+ 10-150 cm &lt; 0.5 ºC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(one camera not correct)</td>
</tr>
</tbody>
</table>

Both low-cost and high-end thermal cameras measured relative temperature changes with high accuracy and absolute temperatures with deviations from the real temperature. Low-cost smart phone based thermal cameras can be a good alternative to high-end thermal cameras for routine clinical measurements, appropriate to the clinical research question, providing the regular calibration checks for quality control and strict protocols should avoid the pitfalls shown in this study.
6. REFERENCES


