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In-Field-of-View Thermal Image Calibration System for Medical Thermography Applications

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Abstract Medical thermography has become ever more accessible to hospitals, medical research, and clinical centers with the new generation of thermal cameras, which are easier to use and lower in cost. Some diagnostic techniques using thermal cameras are now regarded as standardized, such as the cold challenge test for Raynaud's phenomenon. The future for medical thermography appears to be improved accuracy, standardization, and establishment as a mainstream medical imaging methodology. Medical thermography standardization, quantitative measurements, image comparison, and multi-center research trials all require thermal cameras to provide a demonstrably traceable, accurate, and reliable temperature output. To this end, the National Physical Laboratory (NPL) has developed a multi-fixed-point source that serves as an in-image calibration system, thereby providing a reliable means for radiometric image validation. An in-field-of-view fixed-point validation system for thermal imaging has successfully been developed, tested, and validated at NPL and has undergone field trials at three clinical centers in the UK. The sources use the phase change

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plateaux of gallium–zinc eutectic, gallium, and ethylene carbonate. The fixed-point sources have an estimated cavity emissivity of greater than 0.998, a plateau longevity of nominally 3 h at ambient conditions, a stability of 0.1°C, or better, over that period, a repeatability of 0.1°C or better, and an estimated temperature uncertainty of ±0.4°C ($k = 2$). In this article, the source specifications and design as well as testing, validation, and field trial results are described in detail.

Keywords Ethylene carbonate · Fixed point · Gallium · Gallium–zinc · Thermal image

1 Introduction

Medical thermographers use thermal imagers to diagnose and monitor patient health. In most applications, thermal images are used for anomalous variations in skin temperature. These applications typically require a thermal imager to have good thermal and spatial resolution. The temperature information is also used for periodic monitoring of patient progress and image comparison in a clinical center and between clinical centers, as well as procedural development and standardization. These applications require a thermal imager to have, in addition to the previous requirements, good medium- to long-term stability and a regular accredited calibration traceable to the International Temperature Scale of 1990 (ITS-90). Without such, any temperature measurements made will carry significant and often unquantified measurement uncertainty.

It is clear that many medical thermography applications do not require absolute temperature measurements (e.g., when used in a purely imaging mode, there is little desire to carry out regular traceable calibrations—other than to ensure that the imager is operating to its full spatial and thermal capability). However, previous work by National Physical Laboratory (NPL) assessing the performance of thermal imagers used in medical thermography identified poor or non-existent traceability to ITS-90 with a temperature dispersion between the imagers in the region of ±2°C [1]. The disparity was much larger than expected by the medical thermography community and would be very significant for any work involving absolute rather than relative temperature measurement, such as standardization, charting patient progress (either of the disease or of the response to treatment), and image comparison in-center and cross-center.

In response to this, NPL has been working with UK medical thermographers to put in place a robust traceability regime [1]. The developments described here are the next step in putting clinical thermography on a firm traceable basis. NPL has developed an in-image fixed-point calibration system, covering the normal body-temperature range (Fig. 1). This system will provide a means of calibrating the image temperature for high-level thermography measurement and thereby introduce increased measurement rigor and confidence while being a tool to aid thermography standardization and national/international comparisons.

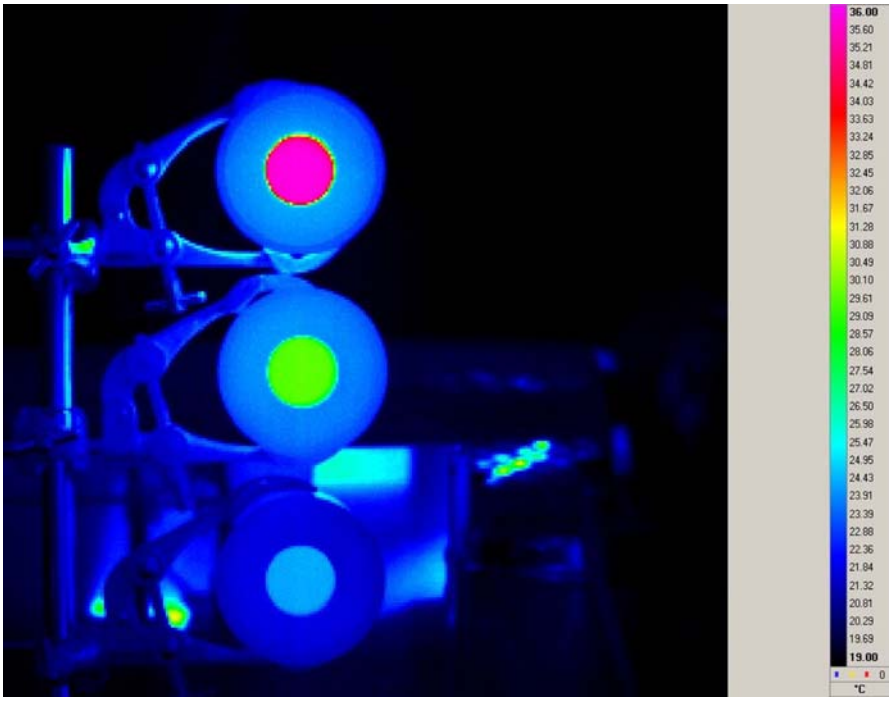

Fig. 1 Thermal image of fixed-point sources in use

2 Measurements

In order to provide an in-image calibration system, it was concluded that three fixed-point blackbody sources would be required to cover the normal medical thermography temperature measurement range, nominally 25–35°C. The normal target-to-imager focal distance in medical thermography is nominally 1 m and a reasonable estimate of array size for imagers would be a minimum 256 × 256. A source aperture size of 26 mm would provide an image size to cover a minimum of 9 pixels (a 3 × 3 block) with which to obtain an average of the temperature from the blackbody aperture. With medical thermography used for a large variety of applications, it was decided that the fixed-point blackbodies should be able to operate without additional temperature control once initiated, allowing them to be orientated around the patient under investigation. A nominal uncertainty requirement of ±0.2°C for the fixed-point temperature was agreed in order to provide an effective calibration system.

A number of materials were considered for the fixed points, both high-purity metals and high-purity organics. The selection was largely governed by previous knowledge of their use as temperature fixed-point materials and their proximity to the required temperature range. The materials finally selected for use were gallium–zinc (∼ 25°C), gallium (29.7646°C), and ethylene carbonate (36.3°C). The gallium–zinc eutectic melting point has never, to our knowledge, been used as a fixed point for thermal metrology. While some work has been carried out in identifying its

characteristics [2], there is limited information concerning its suitability as a fixed point for temperature-measurement applications. The gallium melting point is a very well-known defining fixed point of the ITS-90, and its performance is well-documented. The ethylene carbonate freezing point has also been used as a thermal metrology fixed-point, although not as widely as gallium. It was also used recently in a project to produce an infrared ear thermometry fixed-point validator [3].

Construction material selection was based on fixed-point material compatibility and surface emissivity. While the cavities could be painted with high emissivity paint, it was concluded that this would decrease their overall suitability for use in a clinical environment. The selected cavity construction material was black Teflon (PTFE). This was known to be compatible with the proposed fixed-point materials, providing a robust fixed point with a high surface emissivity [3].

The blackbody cavity design comprised a cylindro-cone with dimensions of 150 mm in length, 26-mm aperture diameter, and a 120° cone for the back wall. The cavity emissivity, for isothermal conditions, was calculated to be 0.9983 using the previously determined Teflon (PTFE) surface emissivity value, over the 8–13 μm range, of 0.79 [3]. The fixed-point cells were constructed by Isothermal Technology Ltd.

The validation testing consisted of repeatability, stability, precise temperature definition, and uncertainty estimation. Dry block Peltier coolers/heaters were used to heat/cool the fixed-point cells. Several preliminary measurement runs were performed to establish the controller settings and initiation procedure for each fixed-point cell. A Land Cyclops C300 IR thermometer, which has an operating wavelength of 8–13 μm, was used as the transfer radiation thermometer and the NPL's ammonia heat-pipe blackbody was used as the comparison blackbody [4].

For the gallium-based fixed points, the procedure was to initially cool the fixed point to 10°C for 2–4 h using the Peltier heater/coolers to ensure that the fixed-point material was completely frozen. Each fixed-point cell was then ramped to a temperature just above its melting-point temperature. At this stage, the cells were then either left to pass straight through their melting plateaux, taking approximately 4–5 h, while being monitored with a Land Instruments Cyclops 300 (C300) IR thermometer mounted vertically above the fixed point, or alternatively, the cells were removed from the Peltier unit after having completed approximately 2–3 h of their plateaux, and then monitored using the C300 thermometer mounted horizontally.

The initial measurements were used to determine controller settings for the Peltier units and to measure plateau stability. The subsequent measurements were used to determine the fixed-point temperature, repeatability, and longevity of plateaux. In this second case, the C300 was used to compare the fixed-point source to the NPL ammonia heat-pipe blackbody.

The procedure for initiating the ethylene carbonate fixed point was as follows. While solid, the cell was placed into a Dewar containing water at approximately 75°C, enough to cover almost the entire fixed point, leaving only about 1 cm at the top of the fixed point uncovered. After 1 h, the pre-boiled water was replaced with fresh hot water. At this point, the fixed-point cell was inverted a number of times to mix the fixed-point material. After a further hour, the fixed point was removed and again inverted to ensure good mixing. The water in the Dewar was replaced with tap water, nominally at 20°C, and the fixed point was again put in the Dewar with the water at

the same level. After a further hour, the water in the dewar was removed and replaced with fresh tap water. After a further hour, the fixed point was removed and initiated using a physical shock (a sharp tap on the bench) and monitored using the C300 IR thermometer.

Several melt and freeze cycles of each fixed-point source were measured. From this data, the fixed points' stability, repeatability, radiance temperature, and overall uncertainty were determined. Following the successful completion of the validation, the fixed points were transported to three clinical centers for field trials. Each clinical center had the fixed-point system for a month, and the fixed points were used in the centers' normal applications.

3 Results

The temperature determination of the fixed-point source was made using the C300 IR thermometer as the transfer radiation thermometer and the NPL ammonia blackbody source as the comparison blackbody source. The average temperatures of the sources were: gallium–zinc = 25.3°C; gallium = 29.8°C; and ethylene carbonate = 35.9°C. An uncertainty of ±0.4°C ($k = 2$) was attributed to each cell (Table 1).

The temperature stability of each of the cells was determined from the standard deviation of a number of fixed-point plateaux (Figs. 2–4). The mean of the standard deviation for all of the melts and freezes was as follows: gallium–zinc eutectic = 0.08°C (14 melts); gallium = 0.08°C (12 melts); and ethylene carbonate = 0.07°C (8 freezes).

The length of the fixed-point melts/freezes that could be expected in normal in situ use was determined over a number of repeat cycles. These were performed with no

Table 1 Uncertainty components for fixed-point blackbody sources

Uncertainty component	Standard uncertainty uncertainty (°C)
Blackbody reference source	0.03
Alignment—reference source	0.06
Alignment—fixed-point source	0.11
Stability—reference source	0.00
Stability—fixed-point source	0.06
DVM accuracy (measuring C300 output)	0.00
SSE reproducibility (C300)	0.02
Residual SSE (C300)	0.13
Resolution (C300)	0.01
Repeatability	0.04
Emissivity of fixed point	0.08
Combined uncertainty	0.22
Expanded uncertainty ($k = 2$)	0.44

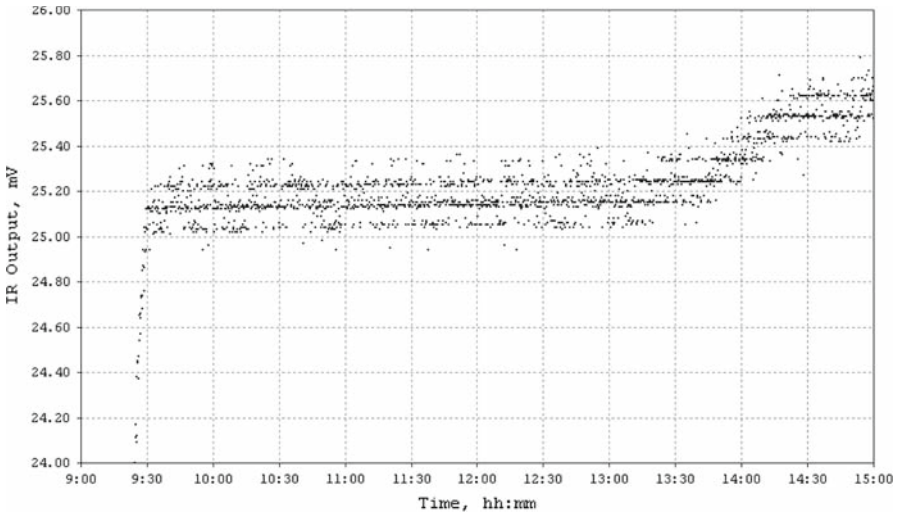

Fig. 2 Typical gallium–zinc fixed-point melt

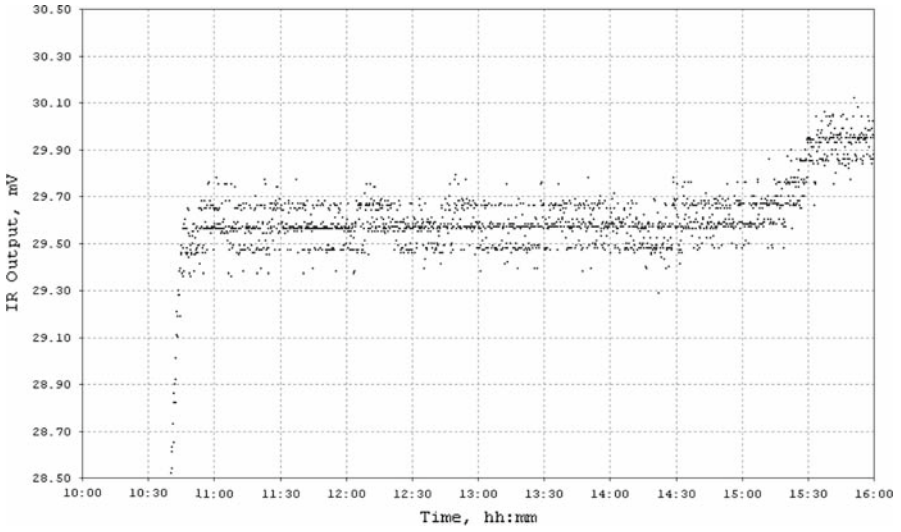

Fig. 3 Typical gallium fixed-point melt

insulation and in typical environmental conditions of ambient humidity and temperature. These results could, therefore, be thought of as worst case. The typical melt plateaux were: gallium–zinc eutectic = 3–4 h; gallium = 3–4 h; and ethylene carbonate = 1–2 h

The repeatability of the fixed-point cells was determined from the standard deviation of the mean for a number of precise temperatures determined from plateau melts/freezes: gallium–zinc eutectic = 0.11°C (7 melts); gallium = 0.09°C (5 melts); and ethylene carbonate = 0.06°C (5 freezes).

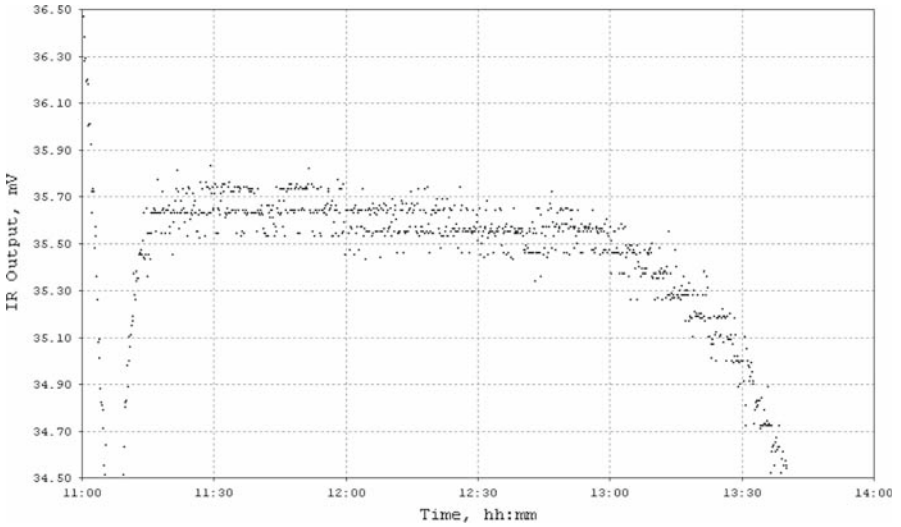

Fig. 4 Typical ethylene carbonate fixed-point freeze

The clinical centers carrying out the field trial measurements reported that the fixed-point cell temperature performance was found to be satisfactory within the performance of the measurement instruments. The longevity of the plateaux for each fixed point was measured both with and without insulation, and the time periods were found to be nominally 2 and 4 h, respectively. It was commented that, in a clinical thermography environment, a 2-h plateau would probably not be sufficient, especially in consideration of the considerable time spent on fixed-point cell preparation—an automated system should help to remove this issue.

The fixed-point sources were used as validation sources in cold challenge hand tests with some success. It was decided that a specific mount would have to be constructed to enable the hands and the cells to be aligned on the same focal plane. The main points of criticism were the un-automated fixed-point cell preparation, the lack of an alignment mount for the fixed points, and the aperture size could potentially require enlargement.

4 Conclusions

Three fixed-point cells for the in-field-of-view calibration of thermal imagers, for use in medical applications, have been successfully constructed, tested, and validated. They successfully provide a means of calibrating thermal images by being operated in the field of view during measurement of a subject. The final uncertainty determination of the fixed-point cells was higher than expected, but the largest uncertainty components come from the transfer radiation thermometer used. Further work will be carried out with a transfer radiation thermometer having better target definition, temperature resolution, and stability, and it is envisaged that the uncertainties will be significantly reduced, maybe by as much as a factor of two.

Field trials of the sources have been successfully carried out. The feedback from the clinicians was largely positive concerning the capability of the fixed-point sources. There were no technical problems with the performance capability of the fixed-point sources; the plateau length, temperatures, and uncertainties were all fit-for-purpose. Suggestions were made concerning the fixed-point initiation and control systems. The fixed-point system was a proof-of-concept; therefore, the initiation and control systems were simple and were not optimized as a commercial system. The field trial results will be reported in more detail in a future paper to be written by the authors.

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