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Graphical user interface design for a calibration device for infrared tympanic thermometers

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This study presents the development of a laboratory calibration device for infrared tympanic thermometers (ITTs), incorporating a high-stability gray-body cavity as an approximation to a blackbody radiation source. Particular emphasis is placed on the design of a graphical user interface (GUI) developed under a user-centered design framework. The interface was iteratively refined through field observations, usability testing, and direct collaboration with healthcare professionals and calibration technicians. The GUI structures the calibration process into four sequential phases - selection, warm-up, calibration, and cooling - using color coding, animated feedback, and high-resolution temperature controls with a minimum resolution of 0.01 °C. Usability evaluations demonstrated high levels of intuitive interaction, reduced cognitive load, and efficient task execution. The visual design contributed to safe operation by clearly communicating system status and preventing common user errors. This work introduces an innovative interface approach within the field of medical metrology and proposes transferable design principles applicable to other precision calibration instruments. The results highlight the importance of integrating human–machine interaction design with metrological rigor to improve transparency, efficiency, and safety in both laboratory and clinical environments.

KEYWORDS
calibration, graphical user interface, healthcare, infrared tympanic thermometer, medical metrology

1 Introduction

Body temperature is a vital sign regularly measured in hospital settings to assess patients' health status, facilitate diagnosis, and guide treatment. Normal body temperature ranges from 36.5 °C to 37.5 °C. Upward deviations from this range causes fever, which requires prompt attention. To obtain reliable body temperature measurements, healthcare professionals need accurate and precise thermometric devices. The reference method used for determining body temperature is the direct measurement of blood temperature. In clinical practice, this is achieved through invasive techniques that estimate core body temperature via measurements in the esophagus, nasopharynx, or urinary tract. Although these methods offer high accuracy, their invasive nature limits their applicability, particularly in large-scale screening scenarios or situations requiring minimal patient contact, such as during the COVID-19 pandemic (Goh et al., 2021).

In response to these limitations, non-contact and minimally invasive thermometry technologies have gained prominence. These approaches reduce patient discomfort and minimize the risk of cross-contamination, contributing to improved infection control (Mogensen et al., 2018). In this context, the World Health Organization has promoted indirect temperature measurement methods as part of public health strategies for rapid fever screening and early detection of infectious diseases. Among these technologies, non-contact infrared thermometers (NCITs) have been widely adopted for their speed and ease of use (Zhao and Bergmann, 2023).

NCITs provide greater comfort and are less invasive for the patient than other devices, as they determine temperature from skin radiation. However, these measurements may fluctuate due to environmental conditions at the measurement site, such as ambient temperature, relative humidity, and incent radiation.

The interior of the ear offers a more protected location for obtaining accurate body temperature because these external fluctuations have less influence on the reading. Consequently, tympanic thermometers have become widely used in the medical community as a reliable reference for body temperature measurement. Infrared tympanic thermometers (ITTs) detect infrared radiation emitted by the tympanic membrane and convert it into an electrical signal that is interpreted as a temperature reading (Mah et al., 2021). Tympanic thermometers are popular due to their fast response time and ease of use, making them a viable option for temperature screening.

1.1 Anatomical measurement point

The auditory canal is a gently curved tube about 35 mm long in adults and is located close to the hypothalamus, the brain's temperature control center, which lies directly beneath the cerebral cortex. Because the hypothalamus shares its blood supply (via the common carotid artery) with the relatively nearby tympanic membrane, the auditory canal is considered an ideal site for obtaining an accurate indication of core body temperature (Gasim et al., 2013; Cascetta, 1995).

1.2 Infrared tympanic thermometer components

An ITT typically consists of an optical probe, an infrared sensor, a compensating internal temperature sensor, a signal processing circuit, and a display unit. The tip of the optical probe (sensitive in the wavelength range from approximately 8 μm and to μm) is inserted into the external auditory canal. The instrument measures the intensity (radiance) of infrared radiation emitted by the tympanic membrane and the skin of the inner auditory canal and determines the temperature of the measurement site using Planck's law of thermal radiation (Ishii, 2008; Figure 1).

1.3 Laboratory calibrator principle

Calibration of the ITT is performed with respect to the temperature reading it reports when viewing a gray-body cavity that approximates a blackbody source at a known calibration temperature. In this case, the relevant radiative source is the gray-body cavity of the laboratory calibrator.

According to the requirements of the relevant standards (ASTM E1965-98, EN 12470-5), an ITT must have an accuracy of ±0.2 °C over its operating range of 35.5 °C to +42 °C, or ±0.3 °C outside this range (ASTM standards 1998 designation E 1965–1998, 1998; En, 2003; International Organization for Standardization, 2017; ASTM International, 2016; International Electrotechnical Commission, 2017).

2 Operating principle of the laboratory calibrator

The operating principle of the laboratory calibrator is based on radiation thermometry and is theoretically grounded in Planck's law of thermal radiation, which describes the spectral distribution of electromagnetic radiation emitted by an ideal blackbody as a function of its absolute temperature. According to this law, the spectral radiance Bλ(T) depends on both wavelength and temperature and can be expressed as:

$$B\lambda(\lambda,\mathrm{T}) = \left(2\cdot \mathrm{h}\cdot \mathrm{c}^2\right) / \left(\lambda^5 \cdot \left(\exp\left(\mathrm{h}\cdot \mathrm{c} / \left(\lambda\cdot \mathrm{k}\cdot \mathrm{T}\right)\right) - 1\right)\right)$$

where:
$h = 6.62607015 \times 10^{-34}$ J·s (Planck constant)
$c = 2.99792458 \times 10^{8}$ m/s (speed of light in vacuum)
$k = 1.380649 \times 10^{-23}$ J/K (Boltzmann constant), as recommended by the CODATA 2022 fundamental constants (Mohr et al., 2025).

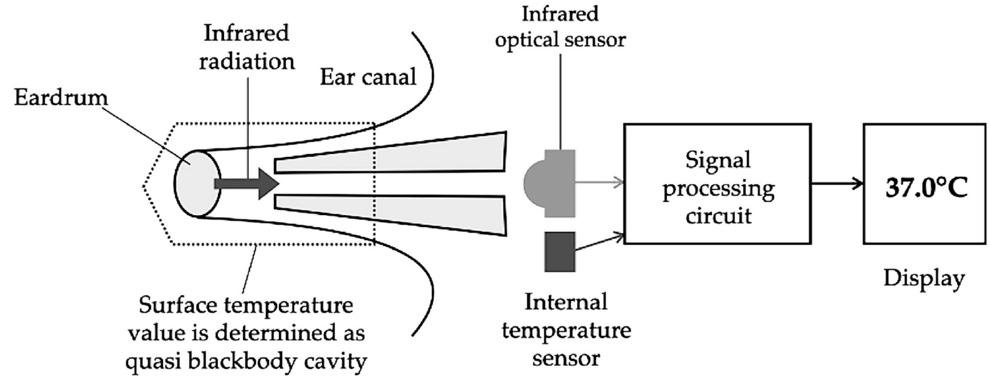

FIGURE 1
Operating diagram of an ITT (based on Ishii, 2008).

From these, the first and second radiation constants are defined as:

$$C1 = 2hc^2 = 1.191042972 \times 10^{-16}\,\mathrm{W{\cdot}m^2/sr}$$

$$C2 = hc/k = 1.438776877 \times 10^{-2}\,\mathrm{m{\cdot}K}$$

As temperature increases, the emission peak shifts toward shorter wavelengths in accordance with Wien's displacement law, while the total emitted radiative power increases proportionally to T^4, as described by the Stefan–Boltzmann law.

In practice, an ideal blackbody ($\varepsilon = 1$) does not exist, so laboratory calibration systems employ gray-body cavities with high emissivity (typically $\varepsilon \geq 0.95$) that approximate the radiative behavior of a perfect blackbody. The calibrator's cavity consists of a blackened, thermally controlled enclosure that provides uniform radiance and temperature stability (Figure 2).

The blackbody cavity employed in the calibrator is a cylindrical, blackened metallic enclosure designed to approximate blackbody radiative behavior within the spectral range of infrared tympanic thermometers (8–14 μm; Figure 3). The cavity has an internal depth of 111 mm and an aperture diameter of 39 mm, resulting in a length-to-diameter ratio that promotes multiple internal reflections and high effective emissivity. Based on its geometry and surface treatment, the effective emissivity of the cavity is estimated to be greater than 0.999 over the operating temperature range (Figure 4).

Thermal uniformity of the gray-body cavity was assessed in terms of radiometric temperature uniformity along the effective optical axis of the cavity, which corresponds to the field of view (FOV) of infrared tympanic thermometers during calibration. This approach is consistent with the intended use of the cavity as a reference radiation source, where the relevant quantity is the uniformity of the emitted radiance observed by the thermometer rather than the absolute wall temperature distribution.

Uniformity measurements were performed under steady-state conditions using a traceable reference radiation thermometer positioned coaxially in front of the cavity aperture. Radiance temperature readings were acquired at several axial positions along the optical axis by varying the measurement distance while maintaining alignment with the cavity center. This method allows evaluation of axial radiometric gradients within the effective radiating field seen by the instrument under test.

In addition, a calibrated contact thermometer inserted from the rear of the cavity toward the cavity bottom was used exclusively for temperature control and internal verification of thermal stability at the cavity base. This sensor configuration does not allow direct measurement of temperature gradients along the cavity walls; however, wall-temperature uniformity is not a limiting factor for calibration, provided that the effective radiating field remains isothermal within the instrument's field of view.

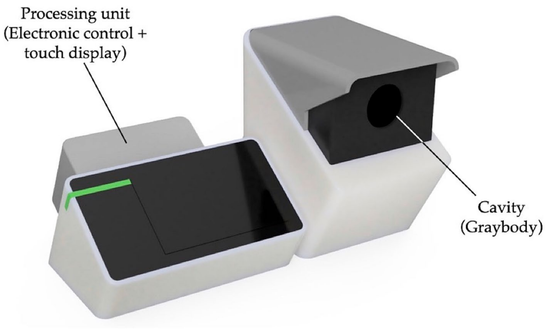

FIGURE 2
Formal design proposal for the laboratory calibrator.

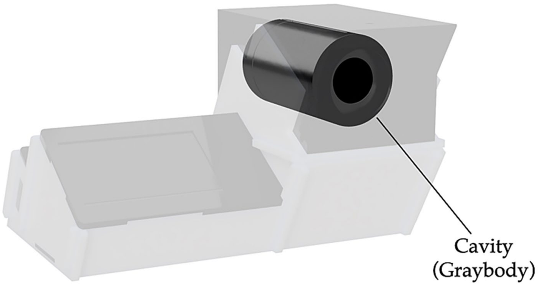

FIGURE 3
Location of the cavity inside the calibration equipment.

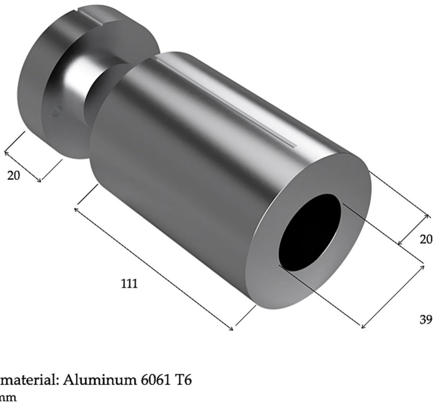

FIGURE 4
Cavity measurements.

The observed axial radiance temperature variations were smaller than ±0.03 °C over the evaluated positions, which is below both the short-term instability of the cavity and the combined expanded uncertainty of the calibration process. Consequently, axial non-uniformity does not represent a dominant contribution to the overall uncertainty budget.

Considering that clinical infrared tympanic thermometers typically exhibit maximum permissible errors of ±0.2 °C, the measured radiometric uniformity of the cavity satisfies international metrological recommendations for reference radiation sources, including the requirements outlined in OIML R 147. The contribution of cavity non-uniformity was therefore treated as negligible relative to other uncertainty components, such as sensor calibration, emissivity estimation, and environmental influences.

In addition, the system allows the insertion of a contact temperature sensor through the rear section of the cavity, enabling temperature measurements close to the cavity bottom. This feature supports internal verification of the thermal conditions in the region corresponding to the effective radiating area.

The internal temperature is regulated through a closed-loop control system, allowing reproducible reference conditions for infrared tympanic thermometers (ITTs). When the ITT is directed toward the cavity aperture, it detects the emitted infrared radiance, which corresponds to the known temperature of the cavity. Comparing the measured signal to this reference allows the determination of measurement error and uncertainty, ensuring metrological traceability in accordance with the principles described by Cárdenas-García and Méndez-Lango (2015). These authors demonstrated that radiometrically calibrated flat-plate or cavity sources provide reliable reference conditions for radiation thermometers. This principle is also consistent with the requirements established by OIML R 147 (OIML, 2016) and the BIPM Best Practice Guide for Infrared Ear Thermometers [Bureau International des Poids et Mesures (BIPM), 2021], which emphasize the use of isothermal, high-emissivity cavities to achieve uniform radiation fields and low uncertainty during calibration.

In summary, the laboratory calibrator operates by generating a stable, uniform field of infrared radiation within a gray-body cavity as an approximation to a blackbody source. The cavity radiates infrared energy from its blackened interior in a thermally stable and constant manner, simulating the characteristics of an ideal blackbody. The emitted temperature is measured by an ITT during calibration, providing quantitative metrological parameters such as measurement error and uncertainty. These data allow assessment of instrument performance and determination of its suitability for clinical or industrial applications. Fundamentals physical constants are taken from CODATA 2022 as adopted by BIPM (Mohr et al., 2025).

To achieve the desired reference conditions, an electrical resistance heater uniformly heats the blackened metal cavity until the selected calibration temperature is reached. After an initial warm-up period of approximately 15 min, the cavity exhibits a temperature instability of 0.025 °C ($k = 1$) and a temperature drift of 0.014 °C under steady-state conditions, values that comply with the performance requirements specified in OIML R 147. These parameters were experimentally verified following Kapter's internal metrology laboratory procedures (Kaplun, 2021), as documented in calibration certificate No. LTR-000850.

Cavity temperature is monitored by a reference thermometer inserted from one end toward the center of radiating surface. The interface, which communicates with both the internal electronics and the user, receives the current temperature of the gray-body cavity from the control sensor. This sensor sends a signal to the temperature controller, which monitors and regulates the cavity temperature and, when necessary, activates the heater to reach and maintain the desired setpoint. The gray-body cavity is thus continuously monitored and controlled as the primary reference element of the system.

The calibration resolution can be adjusted according to the characteristics of the instrument under test and expected measurement uncertainty, ensuring that the objective of the calibration is met. In accordance with good metrological practice, the resolution of the calibrator should be at least 10 times finer than of the thermometer being calibrated; a setting of 0.01 °C therefore provides a clear advantage when using the calibrator as a reference instrument. Through the touchscreen, the resolution can be set to 1 °C, 0.1 °C, or 0.01 °C (units, tenths, or hundredths of a degree Celsius).

This approach is technically supported by the Noise Equivalent Temperature Difference (NETD), which describes how internal electrical noise affects temperature indication. For infrared ear thermometers (IRETs), the NETD is generally lower than 0.1 °C, confirming that a finer calibration resolution is meaningful and not limited by instrument noise [Bureau International des Poids et Mesures (BIPM), 2021].

Once the resolution and target temperature have been selected, the device begins its warm-up process. It requires approximately 30 min to reach 35 °C. Throughout this period, the visual interface changes color and the device to emit audible alerts according to system status. When the desired temperature is reached (indicated by a green screen), the operator positions the ITT in front of the gray-body cavity and acquires at least three consecutive readings. In Kapter's experimental implementation, between 10 and 13 readings were taken per calibration point.

Each measurement series is recorded in a spreadsheet, together with ambient conditions such as the ambient temperature (laboratory air temperature), background temperature (thermal environment temperature surrounding the ITT that may affect its internal infrared sensor), relative humidity, and other relevant parameters. Variations in these conditions can influence the readings due the electronic characteristic of the infrared sensor. The procedure is repeated for all calibration points, typically 3 to 5 temperatures per thermometer.

The recorded data are processed and analyzed in a spreadsheet, and calibration certificate is generate automatically using dedicated software. This documentation provides end user with essential information on device thermometer performance, indicating whether thermometer operates within its technical specifications or is out of tolerance and should be withdraw from service (Kaplun, 2021).

During calibration, the ITT is positioned coaxially in front of the cavity aperture at a fixed distance of approximately 30–50 mm, or in direct contact with the positioning guide, depending on the model under test. The aperture diameter is designed to fully cover the field of view of the ITT sensor, minimizing edge effects and stray radiation (Figure 5). This alignment ensures that the detector receives radiation predominantly from the cavity interior. Clear positioning guidelines are provided to the operator to reduce variability due to misalignment and to ensure repeatable and accurate calibration conditions.

2.1 Classification and scope

The infrared tympanic thermometer calibration device is considered a support or accessory equipment with no assigned risk level, since it does not interact with the patient and has no direct clinical use. Its application is limited to metrological control and laboratory verification, and therefore it is not subject to sanitary registration.

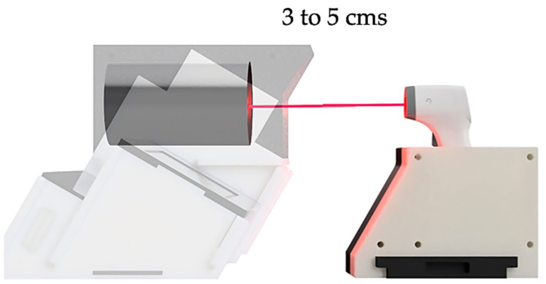

FIGURE 5
Arrangement of measuring equipment.

2.2 Metrological characterization of the gray-body calibration source

To ensure the metrological rigor of the proposed calibration device, the performance of the gray-body cavity used as the reference radiation source was independently characterized. This assessment supports the reliability of the calibration process managed through the graphical user interface (GUI) and establishes traceability under clinically relevant operating conditions for infrared tympanic thermometers.

A. Normative framework and definition of short-term instability.

The evaluation of short-term temperature instability was carried-out in accordance with OIML R-147:2016, which provides guidance for the calibration and verification of blackbody radiators over the temperature range from −50 °C to 2,500 °C. According to this document, the temperature instability at each calibration point is quantified under steady-state conditions as the statistical dispersion of repeated temperature readings.

For each set temperature T_set (typically at low, medium, and high values within the operating range), once steady-state conditions are achieved, n temperature readings T_i are recorded at defined time intervals over a specified observation period. The arithmetic mean temperature is then calculated as:

$$\mathrm{T\_a}=\left(1/\mathrm{n}\right)\cdot\Sigma\left(\mathrm{T\_i}\right).$$

and the experimental standard deviation is calculated as:

$$\sigma\left(\mathrm{T\_i}\right)=\left[1/\left(\mathrm{n}-1\right)\cdot\Sigma\left(\mathrm{T\_i}-\mathrm{T\_a}\right)\hat{}\,2\right]\hat{}\left(1/2\right).$$

This standard deviation represents the short-term variation of the thermal control at the evaluated calibration point. OIML R-147 further recommends calculating the standard uncertainty of the mean temperature as:

$$\mathrm{u}\left(\mathrm{T\_a}\right)=\sigma\left(\mathrm{T\_i}\right)/\sqrt{}\,\mathrm{n}.$$

which is treated as the statistical contribution associated with temperature stability over the observation interval.

The instability (or stability) of the blackbody radiator is reported in terms of an expanded uncertainty defined as:

$$\mathrm{U\_inst}=\mathrm{k}\cdot\sigma\left(\mathrm{T\_i}\right).$$

where k is the coverage factor (typically *k* = 2, corresponding to a confidence level of approximately 95%). When instability values obtained using an external reference thermometer and the internal thermometer of the blackbody radiator are compared, a conservative approach is adopted by selecting the larger of the observed dispersions.

As a functional conformity criterion for the temperature control system, OIML R-147 states that if the measured standard deviation σ(T_i), exceeds one half of the instability value declared by the manufacturer in the technical documentation of the blackbody radiator, the radiator shall be considered non-conforming at that operating point.

B. Experimental methodology.

The gray-body cavity integrated into the calibration device was evaluated at a set temperature of 42 °C, corresponding to the upper limit of the clinically relevant temperature range for infrared tympanic thermometers. Measurements were performed under steady-state conditions, with the temperature control system operating continuously and without setpoint adjustments throughout the data acquisition period.

Temperature measurements were obtained using two independent and traceable reference instruments: (i) a calibrated reference radiation thermometer, corrected for its calibration error, and (ii) a calibrated reference contact thermometer. For each instrument, temperature readings were recorded at 1 min intervals over a total duration of 15 min, yielding 15 measurements per data series.

C. Experimental results and instability calculation.

The experimental temperature readings obtained during the stability assessment at 42 °C are summarized in Table 1. The table presents the mean values, standard deviations, and expanded uncertainties of the measurements obtained with both the reference radiation thermometer and the reference contact thermometer (15 data points from each), together with the corresponding statistical indicators.

For the reference radiation thermometer, the recorded temperature readings yielded a mean value of 42.02 °C with an experimental standard deviation of 0.04 °C. The reference contact thermometer measurements yielded a mean value of 42.00 °C with an experimental standard deviation of 0.02 °C, as detailed in Table 1.

In accordance with OIML R-147, a conservative approach was adopted by selecting the largest observed standard deviation as representative of the short-term instability of the gray-body cavity. Accordingly, the instability at 42 °C was quantified as σ_inst = 0.04 °C, corresponding to an expanded instability of U_inst = 0.08 °C for a coverage factor *k* = 2.

D. Interpretation and section closure.

Clinical infrared tympanic thermometers typically exhibit maximum permissible errors on the order of ±0.2 °C. International metrological practice recommends that the uncertainty associated with the calibration source be significantly smaller than that of the instrument under calibration. The measured expanded instability of 0.08 °C

TABLE 1 Summary of temperature stability measurements at 42 °C.

Statistical indicators	Radiation thermometer reading (°C)	Contact thermometer reading (°C)
Mean value (°C)	42.02	42.00
Standard deviation (°C)	0.041	0.017
Expanded uncertainty (k = 2; °C)	0.083	0.034*

*The expanded uncertainty for the contact thermometer corresponds to U = kσ with k = 2. It is reported here for completeness but was not used as the representative instability, in accordance with the conservative criterion of OIML R-147.

therefore satisfies internationally accepted criteria for use in the calibration of infrared tympanic thermometers.

The results of this metrological assessment confirm that the thermal behavior of the gray-body cavity does not constitute a limiting factor in the calibration process. Consequently, the graphical user interface described in the previous sections operates on a thermally stable and traceable reference source, allowing subsequent usability and performance evaluations to be interpreted independently from hardware-related thermal effects.

Having established the metrological validity and short-term thermal stability of the gray-body calibration source under controlled conditions, the following section describes the practical calibration conditions, internal procedures, and traceability framework under which the device is operated during routine calibration of infrared tympanic thermometers.

2.3 Calibration conditions and traceability

Compliance with international standards was verified through calibration tests performed using Kapter's documented and controlled internal procedures (PR-LT-002, IT-LT-002-01, IT-LT-001-03). These procedures define standardized calibration methods, uncertainty evaluation, and result documentation, thereby ensuring traceability and reproducibility. They are aligned with established metrological practices for infrared radiation thermometry and are consistent with the calibration methodology proposed by Kaplun (2021), which emphasizes integrating thermal stability assessment, radiometric reference definition, and uncertainty control to ensure reliable, precise, and traceable calibration of radiation thermometers.

Calibration was conducted within the clinical temperature range from 30 °C to 44 °C using a cavity-type radiating source with an effective emissivity close to unity and spectral compatibility with infrared tympanic thermometers operating in the 8–14 μm band. The calibration source corresponds to the gray-body cavity characterized in the previous section, whose metrological validity and short-term thermal stability were independently demonstrated in accordance with OIML R-147.

Thermal stability during routine calibration was evaluated under steady-state operating conditions after a 15-min warm-up period. Under these conditions, a typical operational temperature instability of 0.025 °C and a temperature drift of 0.014 °C were observed. These values represent the observed operational performance of the system during routine calibration and are consistent with, though not intended to replace, the conservative short-term instability assessment derived from the formal metrological characterization presented in the previous section. An average correction of 0.06 °C was applied during calibration to account for systematic effects identified in the traceability chain.

The combined expanded uncertainty of the calibration was evaluated as ±0.33 °C ($k = 2$). This uncertainty level is consistent with the permissible error limits specified for clinical infrared tympanic thermometers and supports the suitability of the calibration device as a stable and reliable reference source for clinical applications. The uncertainty evaluation systematically accounts for the dominant influence quantities affecting the determination of the effective radiometric temperature, including the effective emissivity of the cavity, spatial temperature uniformity and temporal stability, the accuracy, resolution, and drift of the contact reference temperature sensor, as well as uncertainties associated with thermal coupling between the sensor and the cavity.

Additional contributions to the uncertainty budget arise from ambient conditions, reflected radiation, heat losses due to conduction and convection, and the repeatability of the thermal control system. In this context, ambient temperature refers to the laboratory air temperature, while background temperature corresponds to the thermal environment surrounding the infrared tympanic thermometer, including nearby surfaces that may contribute additional radiative flux. Variations in background temperature can influence the internal infrared sensor of the thermometer through radiative coupling, potentially affecting measurement results. For this reason, both parameters are monitored and recorded during calibration to support uncertainty evaluation and result traceability.

Cavity temperature monitoring and control are performed using contact-type thermometers, typically platinum resistance thermometers (Pt100 RTDs, Class A) or calibrated thermocouples, selected according to the required accuracy and thermal stability. Platinum resistance thermometers are preferred due to their low drift, good repeatability, and well-established traceability to national temperature standards. The selection and implementation of the contact temperature sensor directly impact the achievable measurement uncertainty and are therefore aligned with the intended calibration accuracy of infrared tympanic thermometers.

2.4 Advantages of the laboratory calibrator over other calibration instruments

The calibration instrument features the following innovations compared to existing commercial instruments:

1. Interchangeable Gray-Body Cavities.

The device supports interchangeable gray-body cavities with different internal bottom geometries, including single-piece and two-piece designs. Single-piece cavities are manufactured as monolithic components with fixed geometry, whereas two-piece cavities incorporate interchangeable plugs that define the cavity bottom. This architecture enables systematic evaluation and comparison of cavity geometries in terms of radiometric performance and measurement accuracy.

2. Contact-Based Temperature Monitoring.

The cavity temperature is monitored using contact-type reference and control thermometers, typically an RTD (Resistance Temperature Detector) or a thermocouple, selected according to the required accuracy and stability. These sensors are inserted through aligned rear or side ports in the removable gray body cavity to ensure proper thermal contact. The achievable precision and accuracy depend on the metrological performance of the selected reference and control thermometers.

3. Integrated Digital Touchscreen Interface.

The calibrator incorporates a dedicated touchscreen-based graphical user interface that enables intuitive operation and

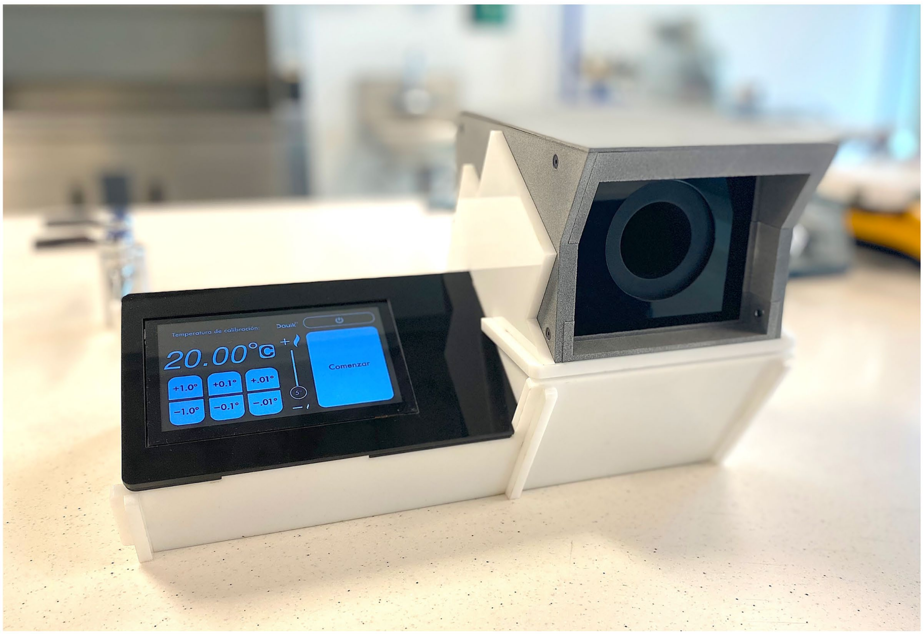

FIGURE 6
Laboratory calibrator for infrared tympanic thermometers (ITTs) in operation. (Front view of the device showing the touch display and the cavity).

real-time visualization of system status. To the authors' knowledge, this is the first commercial calibration device for infrared tympanic thermometers to integrate a fully graphical, phase-based interface (Figure 6).

4. Modular Physical Architecture.

The physical structure consists of two distinct bodies, separating the heating and radiating components from the control and interaction area. This configuration ensures mechanical stability and proper alignment of the instruments under test, while providing ergonomic access to the touchscreen interface.

5. Embedded Control via Single-Board Computer.

A Raspberry Pi single-board computer (SBC) provides embedded control and user interaction through the touchscreen. This implementation simplifies temperature setting, monitoring, and calibration workflows, and facilitates future updates or customization of control algorithms and user interfaces.

6. Compliance with International Metrological Guidance.

The radiation source is designed to comply, by technical analogy, with international specifications applicable to clinical infrared thermometers, particularly regarding thermal stability, temperature uniformity, repeatability, and metrological traceability-key requirements for reference sources used in calibration and verification processes. These performance characteristics are consistent with international metrological guidance (OIML) and with technical reference standards commonly applied to infrared ear thermometry, including ISO 80601-2-56, ASTM E1965, and UNE-EN-IEC 80601–2-59. This level of compliance supports its use as a laboratory reference source and does not imply clinical application or medical device classification.

7. Broad Applicability.

The calibrator can be used to calibrate and characterize both industrial and clinical infrared thermometers within its operating temperature range, enhancing its versatility across different metrological contexts.

8. Uniform Heating Design.

The device incorporates a silicone heater whose shape and flexibility allow it to fully enclose the blackbody cavity, ensuring uniform heating of the blackened metal component. The heater is also versatile, operating at 110 V and reaching temperatures of up to 100 °C without deformation.

3 User interface development

The development of the graphical user interface (GUI) for the laboratory calibrator was guided by the objective of integrating metrological precision with intuitive human–machine interaction. Unlike conventional calibration devices, which often rely on generic digital controllers, this system required an interface capable of supporting high-resolution temperature control while minimizing operational errors and cognitive load in laboratory environments.

The interface design process was structured around the following research questions:

- How do laboratory technicians interact with calibration equipment during routine workflows?
- What limitations and pain points are present in existing calibration interfaces?

- How can visual feedback and interaction patterns improve accuracy and reduce user error?
- Which feedback mechanisms most effectively communicate system status during calibration?

Addressing these questions ensured that the interface design responded not only to technical requirements but also to the practical realities of laboratory operation.

3.1 Research methodology

The interface was developed using a user-centered design (UCD) that combined qualitative and quantitative research methods. Qualitative techniques were used to obtain in-depth insights into user behavior, workflows, implicit needs, and interaction challenges, while quantitative approaches supported pattern identification and comparison across user profiles (Hosamani, 2022).

Data collection methods included structured interviews, contextual inquiries, direct observation, and technical questionnaires. These instruments were applied primarily in thermography and calibration laboratories, as well as in selected clinical environments where infrared thermometers are routinely used. The mixed-method approach ensured that both experiential and measurable aspects of interface usability were considered during design.

3.2 User research

Field research was conducted in specialized thermography laboratories, most notably at the Kapter ® Engineering Center, in collaboration with professionals with more than 10 years of experience calibrating infrared thermometers (ITTs). Additional observations were carried out at the DIF Health Center in Guadalajara and in private medical offices.

Through structured interviews, shadowing, and observational studies, the research identified:

- Existing calibration workflows and procedural sequences.
- Recurrent difficulties with current interface designs.
- User preferences regarding control mechanisms and visual feedback.
- Mental models associated with the calibration process.
- Environmental factors affecting interface usability in laboratory settings.

Shadowing studies proved particularly valuable, revealing interaction patterns and workflow nuances that were not explicitly articulated during interviews. Observing technicians *in situ* highlighted discrepancies between prescribed procedures and actual practice, reinforcing the importance of contextual research in the design of specialized technical interfaces (Yoo et al., 2015).

3.3 Interface requirements analysis

Based on the results of our research, the following core requirements were defined for the graphical user interface (GUI).

a. Fine temperature control with a minimum resolution of 0.01 °C.
b. Support for measurements in both Celsius and Fahrenheit.
c. Clear visual indicators of system status throughout all calibration phases.
d. Navigation aligned with the logical calibration workflow.
e. Post-calibration adjustment capabilities for verification.
f. Error-prevention mechanisms for critical operations, supported by precise closed-loop temperature control.
g. Visual design optimized to minimize cognitive load.
h. Compatibility with rapid iterative testing and refinement.

Temperature control is achieved using a closed-loop proportional–integral–derivative (PID) controller, which regulates the graybody cavity temperature based on feedback from a contact reference sensor. PID parameters are manually tuned during manufacturing using a trial-and-error approach to ensure stable, non-oscillatory thermal behavior. Automatic self-tuning was intentionally excluded to guarantee predictable and repeatable performance, which is essential in metrological calibration contexts.

Although the system offers flexible user-configurable settings, such as selectable temperature resolution and adjustable calibration sequences, these parameters do not affect the thermal control loop or the radiometric characteristics of the cavity. The graphical user interface operates exclusively at the interaction layer, providing access to predefined and metrologically validated operating conditions. Consequently, interface flexibility does not introduce additional uncertainty sources into the calibration process.

3.4 Interface design process

3.4.1 Design principles

Four design principles guided the interface development:

1. **Intuitive Navigation**: Controls are organized to reflect the sequential calibration workflow, reducing the need for training.
2. **Effective Visual Design**: Color, animation, and visual hierarchy are used to convey system state without reliance on textual explanations.
3. **Responsive feedback**: Real-time visual responses confirm user actions and system transitions.
4. **Consistent design language**: A unified visual system across all screens ensures coherence and predictability (Oulasvirta et al., 2020).

3.4.2 Interface workflow design

The calibration process was divided into four sequential phases, each represented by a dedicated screen and visual state.

3.4.2.1 Selection phase

In the selection phase, the user defines the target calibration temperature. The interface includes:

- Precision buttons enabling adjustments down to 0.01 °C
- A slider for coarse temperature changes (±5 °C), which also serves as a visual boundary indicator
- A clear numerical temperature display with unit notation
- A primary action button to advance to the next phase

Control spacing and element size were carefully designed to reduce input errors, particularly in scenarios where users operate the device while wearing laboratory gloves (Figure 7).

3.4.2.2 Warm-up phase

Once the target temperature is selected, the system enters the warm-up phase. The interface transitions to:

- A red color scheme indicating active heating
- An animated progress indicator showing approach to the target temperature
- Simultaneous display of current and target temperatures
- A cancel option allowing safe interruption of the process

Color and animation reinforce the user's mental model of system progression and clearly differentiate this phase from others (Figure 8).

3.4.2.3 Calibration phase

Upon reaching thermal stability, the system enters the calibration phase, indicated by:

- A green full-screen color scheme signaling readiness
- Prominent display of the stabilized cavity temperature
- Controls for fine post-calibration temperature adjustments
- An option to initiate the cooling phase

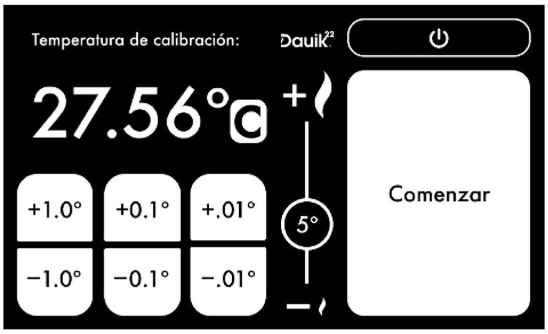
Temperatura de calibración: 27.56°C

FIGURE 7
The screen of the selection and data entry phase. Buttons for temperature increments in hundredths of a degree are visible.


Temperatura actual del equipo: 35.67°C
Temperatura objetivo: 37.56°c
Espere a que el equipo este listo.

FIGURE 8
Warm-up phase screen. The start of this phase is evident when the entire screen changes to a red color.

Post-calibration adjustment controls were included to support verification at multiple temperature points without requiring a full restart of the calibration cycle (Figure 9).

3.4.2.4 Cooling phase

After completing calibration, the system transitions to the cooling phase. The interface provides:

- A distinct color scheme differentiating it from previous phases
- Visual feedback indicating cooling progress
- A confirmation step prior to shutdown to prevent accidental termination

This phase was introduced in response to observed user behavior: premature shutdown was identified as a frequent issue with existing calibration devices, potentially affecting subsequent measurements and hardware longevity (Figure 10).

Although the interface visually represents a sequential workflow, temperature setpoints can be defined independently of previous calibration points. This allows both ascending and descending temperature calibration sequences and enables the assessment of hysteresis effects in infrared tympanic thermometers, a common practice in calibration laboratories.

3.5 Iterative development and testing

The interface was refined through two major iterative design cycles based on user feedback and laboratory testing.


Temperatura actual del equipo: 37.56°C

FIGURE 9
Calibration phase screen.


Apagando equipo

Por favor espere a que se apague la pantalla para presionar el botón de apagado

FIGURE 10
Cooling phase screen.

3.5.1 First iteration

Initial testing led to several improvements:

- Increased temperature resolution from 0.1 °C to 0.01 °C
- Addition of ±5 °C indicators on the slider for rapid adjustments
- Clear display of temperature units (°C/°F; Figure 11)

Progress indicators were redesigned to reflect the increased resolution, improve visual clarity, and align with the device's visual identity (Figure 12). Post-calibration controls were also enhanced to allow faster transitions between calibration points (Figure 13).

In parallel, physical–digital integration testing was carried out to verify compatibility between the GUI and the hardware platform. This phase highlighted the need to optimize response time between physical temperature changes and on-screen updates, improve display visibility under varying lighting conditions, and refine touchscreen placement to better support multitasking during warm-up phase (Figure 14).

3.5.2 Second iteration

A second iteration introduced additional refinements based on laboratory validation:

- Improved color contrast for enhanced readability
- Support for high-resolution numerical displays (e.g., 43.21 °C)
- Enhanced visual feedback during the cooling and shutdown process

A mandatory confirmation step was added before shutdown to prevent accidental interruption of calibration procedures. These refinements addressed issues observed during real-world use and underscored the value of iterative, observation-driven interface design.

4 Results and validation of the graphical user interface

The graphical user interface developed for the laboratory calibrator was validated through usability testing focused on functional clarity, interaction flow, and system comprehensibility. Given the exploratory nature of this study and the specialized context of metrological calibration, validation relied on structured qualitative observation rather than quantitative performance metrics.

Usability testing was conducted with six participants divided into two user profiles: healthcare professionals and technical specialists. Variables such as age and sex were not considered confounding factors because the interaction tasks involved standard procedural operations that are independent of demographic characteristics.

4.1 Participants and testing context

The first group consisted of three healthcare professionals, all women between 40 and 55 years of age, residing in the metropolitan area of Guadalajara, Jalisco. This group included two internal medicine physicians, one affiliated with a major state-level Comprehensive Family Development (DIF) center and one licensed physical therapist working in a community rehabilitation clinic. Participants were selected based on their routine use of temperature measurement devices and their potential to apply the technology in real clinical settings.

The second group consisted of three technical specialists with extensive experience in thermography and medical device calibration: one female doctoral candidate and two male engineers aged 50, 48, and 30 years, respectively. All participants were affiliated with an accredited calibration laboratory or the engineering center where the device was developed, enabling a controlled technical evaluation of the system.

Testing sessions involved executing representative tasks aligned with the operational workflow of the calibrator, including setting target temperatures, monitoring thermal stabilization, performing fine temperature adjustments, and completing the calibration cycle through system shutdown. Healthcare professionals were allowed unrestricted interaction with the device to simulate real-world clinical usage conditions.

4.2 Testing procedure

Interaction with the interface was conducted in an unattended setting, without step-by-step instructions or direct supervision. This approach was intentionally chosen to observe spontaneous user behavior and to identify potential deficiencies in navigation, information architecture, or feedback mechanisms.

Although quantitative metrics such as task completion time or error frequency were not collected, a structured observational framework was applied. Observations focused on:

- User interpretation of interface states and transitions
- Preferred control elements for temperature adjustment
- Points of hesitation or confusion during task execution
- Evidence of learning and operational adaptation over time

This qualitative approach allowed the identification of interaction patterns and areas of cognitive friction that might not emerge through purely quantitative evaluation.

4.3 Usability outcomes

The results indicate that the interface achieved a high level of functional readability. Participants were able to understand the calibration workflow with minimal exploration, demonstrating a short learning curve and progressive mastery of system operation.

Users consistently recognized the sequential structure of the four calibration phases and correctly associated color changes with system status. The combination of visual cues, numerical feedback, and interaction constraints effectively guided users through critical operations without the need for external assistance.

No critical navigation errors or unsafe interactions were observed during testing. Minor exploratory actions, such as repeated adjustment of temperature controls, were interpreted as part of normal familiarization rather than design deficiencies.

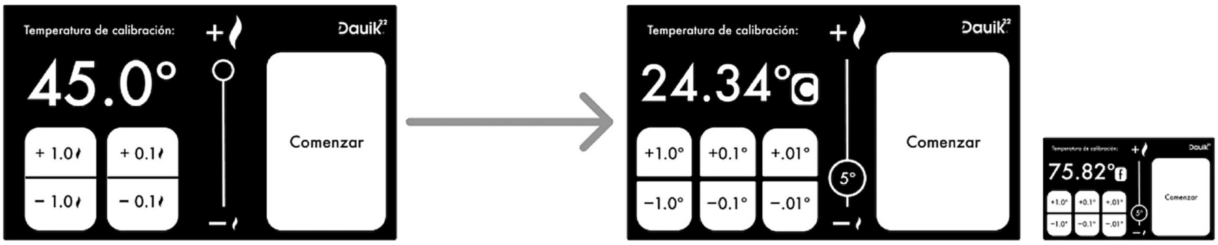

FIGURE 11
Changes made after the first iteration.

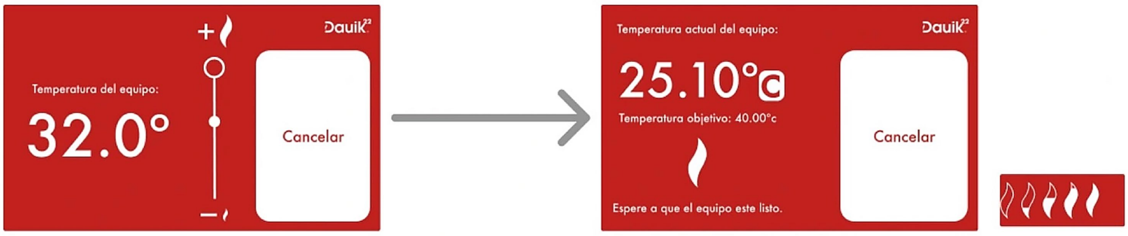

FIGURE 12
Progress indicator improvements.

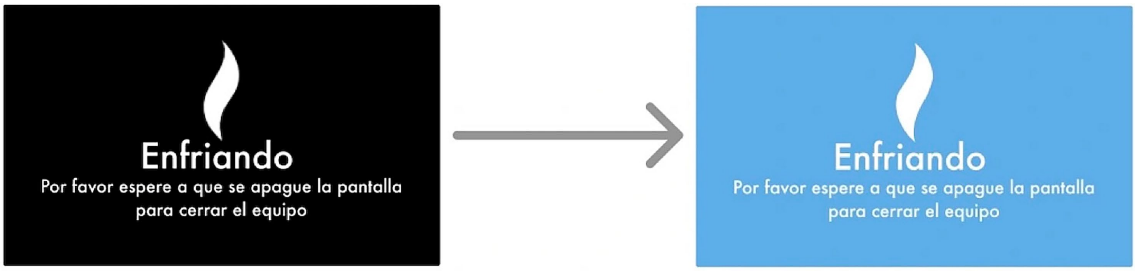

FIGURE 13
Final phase color change.

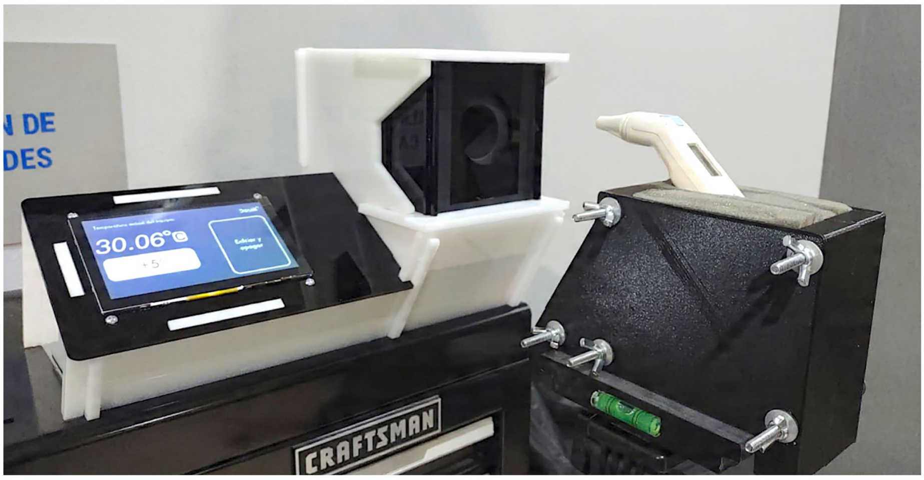

FIGURE 14
Integration testing is in use in the lab.

4.4 User experience achievements

Based on observational analysis and user feedback, the following achievements were identified:

a. A clear four-phase interaction model that intuitively guides users through the calibration process
b. Visual communication strategies that effectively convey system status without requiring technical expertise
c. Fine-resolution temperature controls supporting adjustments from whole degrees to hundredths of a degree (0.01 °C)
d. Safety mechanisms, including confirmation steps, that prevent accidental interruption of critical operations.

Participants noted improvements in workflow efficiency and perceived reliability compared to with previously used calibration systems. The availability of three resolution levels (1 °C, 0.1 °C, and 0.01 °C) was highlighted as a key advantage, allowing the device to be used in both routine commercial calibration and high-precision laboratory contexts.

4.5 Visual design system validation

A consistent visual design system was implemented across all interface screens and validated through user interaction. Key elements included:

- Phase-based color coding for selection, warm-up, calibration, cooling, and shutdown
- Typography and spacing optimized for readability under laboratory lighting conditions
- Interaction components (buttons, sliders, toggles) designed for precision and repeatability
- Animated transitions that reinforce system state changes

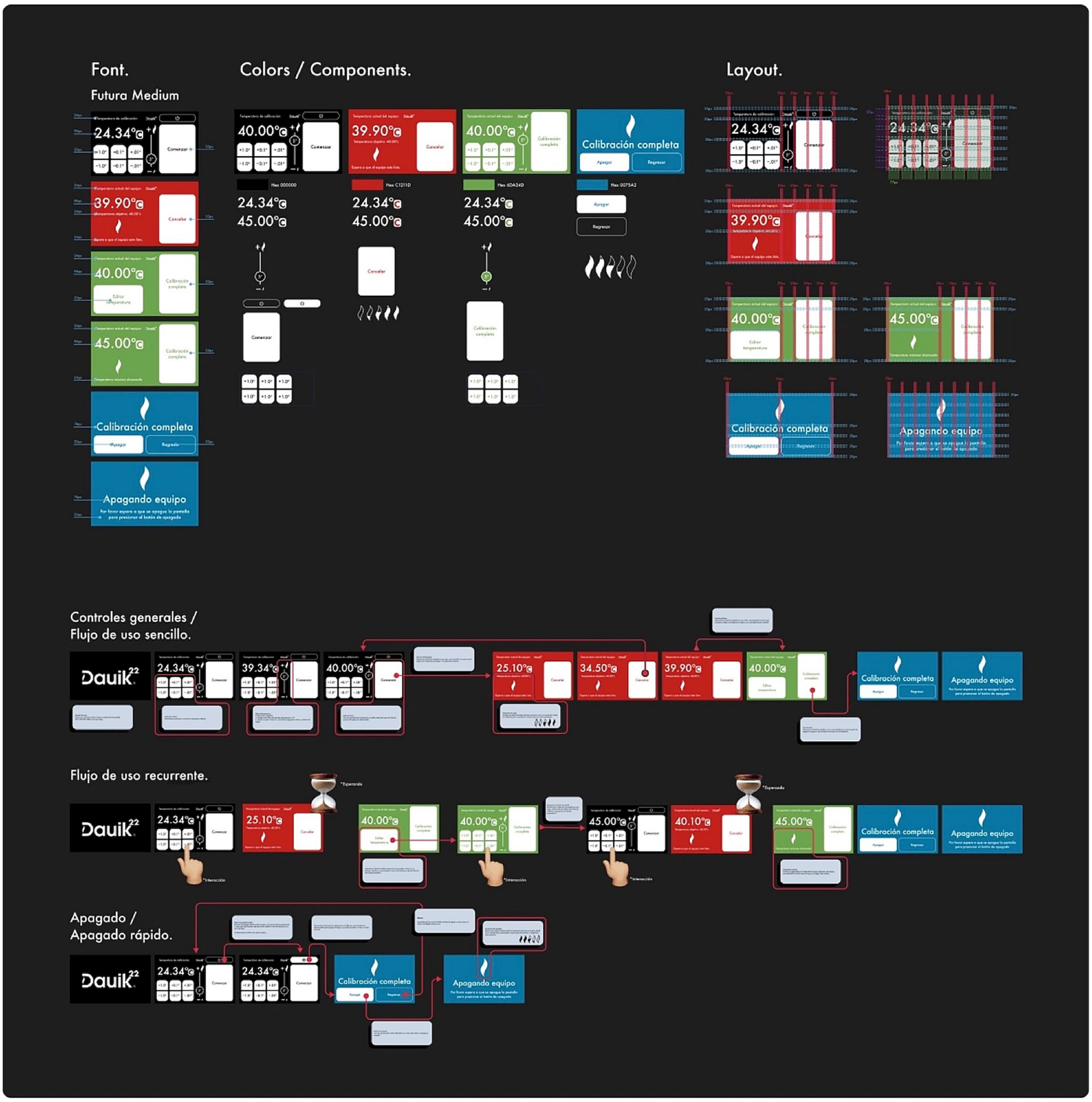

FIGURE 15
Overall visual design system.

Users reported that the visual consistency reduced the need for conscious interpretation of system status, allowing them to focus on calibration tasks rather than interface management. This findings suggests that the design system contributed to reduced cognitive load and improved operational confidence (Figure 15).

4.6 Validation scope and limitations

The validation process confirmed that the interface supports autonomous execution of key calibration tasks by both healthcare professionals and technical specialists. However, the qualitative nature of the study and the limited number of participants constrain the generalizability of the findings.

Future studies should complement these results with quantitative usability metrics, such as task completion time, error rates, and standardized usability scales, to further substantiate the effectiveness and efficiency of the interface. Longitudinal research could also examine the impact of interface design on calibration accuracy and procedural consistency over extended periods of use.

5 Conclusion

This study demonstrates that integrating a user-centered interface design with rigorous metrological principles can substantially improve the usability, transparency, and operational safety of precision calibration equipment. A graphical user interface specifically designed for the calibration of infrared tympanic thermometers was developed and validated on top of a thermally stable, traceable gray-body reference source.

The interface architecture, structured into four sequential phases -selection, warm-up, calibration, and cooling- provides a clear operational model that aligns with established laboratory calibration workflows. The use of the phase-based color coding, animated feedback, and high-resolution temperature control (down to 0.01 °C) enables users to accurately interpret system status, reduces cognitive load, and minimizes the likelihood of operational errors without compromising metrological integrity.

Unlike conventional calibration instruments that rely on generic digital controllers, the proposed system introduces a purpose-designed graphical interface tailored to the specific requirements of infrared radiation thermometry. To the authors' knowledge, this represents the first laboratory calibration device for infrared tympanic thermometers to incorporate a fully graphical, phase-based user interface. This design approach enhances workflow efficiency and accessibility, allowing both calibration specialists and healthcare professionals to operate the device autonomously and with confidence.

Qualitative usability validation with healthcare practitioners and technicals experts confirmed that the interface supports rapid learning, clear interpretation of system states, and safe execution of calibration procedures. Although the evaluation was exploratory and qualitative in nature, the observed interaction patterns indicate that thoughtful interface design can positively influence the effectiveness, reliability, and perceived robustness of metrological procedures.

Future work should extend this research through quantitative usability metrics and longitudinal studies to assess the long-term impact of interface design on calibration accuracy, procedural consistency, and error reduction. The design principles established in this work (intuitive navigation, clear visual communication, responsive feedback, and consistent visual language) are transferable to other medical and industrial calibration instruments. Overall, this study highlights the value of aligning human-machine interaction design with metrological rigor, demonstrating that high-precision instrumentation can achieve technical excellence without sacrificing usability or operational clarity.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MM: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. AR-S: Conceptualization, Supervision, Writing – review & editing. RF-A: Methodology, Supervision, Writing – review & editing. MG-H: Supervision, Writing – review & editing. DV-Z: Conceptualization, Validation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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References

ASTM International (2016). ASTM E1965-98(2016), standard specification for infrared thermometers for intermittent determination of patient temperature. West Conshohocken, Pennsylvania, USA: ASTM International.

ASTM standards 1998 designation E 1965–1998. (1998). Standard specification for infrared thermometers for intermittent determination of patient temperature annual book of ASTM standards 1998. West Conshohocken, PA: ASTM.

Bureau International des Poids et Mesures (BIPM). (2021). Best practice guide: Use of infrared ear thermometers to perform traceable non-contact measurements of human body temperature (3rd version). BIPM. Available online at: https://www.bipm.org/documents/20126/59596925/Best+Practice+Guide+for+Infrared+Ear+Thermometers/52e3d750-f282-beca-8b5d-bfb0d748d304 (Accessed February 6, 2026).

Cárdenas-García, D., and Méndez-Lango, E. (2015). Use of radiometrically calibrated flat-plate calibrators in calibration of radiation thermometers. *Int. J. Thermophys.* 36, 1775–1783. doi: 10.1007/s10765-015-1938-8

Cascetta, F. (1995). An evaluation of the performance of an infrared tympanic thermometer. *Measurement* 16, 239–246.

En, B. (2003) Clinical Thermometers-Part5: Performance of Infra-red ear thermometers (with maximum device)

Gasim, G. I., Musa, I. R., Abdien, M. T., and Adam, I. (2013). Accuracy of tympanic temperature measurement using an infrared tympanic membrane thermometer. *BMC. Res. Notes* 6, 1–5. doi: 10.1186/1756-0500-6-194

Goh, N. W. J., Poh, J. J., Yeo, J. Y., Aw, B. J. J., Lai, S. C., Cheng, J. J. W., et al. (2021). Design and development of a low cost, non-contact infrared thermometer with range compensation. *Sensors* 21:3817. doi: 10.3390/s21113817

Hosamani, S. (2022). User interface and user experience: a review on evaluation, design and research methodology for mobile applications. *Grenze Int. J. Eng. Technol. (GIJET)* 8:936–942.

International Electrotechnical Commission (2017). IEC 80601–2-59:2017 medical electrical equipment - part 2–59: Particular requirements for the basic safety and essential performance of screening thermographs for human febrile temperature screening. Geneva, Switzerland: IEC.

International Organization for Standardization (2017). ISO 80601-2-56:2017 medical electrical equipment - part 2–56: Particular requirements for clinical thermometers for body temperature measurement ISO. Geneva, Switzerland.

Ishii, J. (2008). Improving the reliability of temperature measurements taken with clinical infrared ear thermometers - design and establishment of a new calibration system traceable to the national standards. *Synthesiology English edition* 1, 47–60. doi: 10.5571/syntheng.1.47

Kaplun, M. (2021). Metodología de calibración Dauik® para termómetros de radiación: una propuesta para la confiabilidad, precisión y trazabilidad metrológica. Available online at: https://ciateq.repositorioinstitucional.mx/jspui/handle/1020/507 (Accessed February 6, 2026).

Mah, A. J., Ghazi Zadeh, L., Khoshnam Tehrani, M., Askari, S., Gandjbakhche, A. H., and Shadgan, B. (2021). Studying the accuracy and function of different thermometry techniques for measuring body temperature. *Biology* 10:1327. doi: 10.3390/biology10121327

Mogensen, C. B., Wittenhoff, L., Fruerhøj, G., and Hansen, S. (2018). Forehead or ear temperature measurement cannot replace rectal measurements, except for screening purposes. *BMC Pediatr.* 18, 1–6. doi: 10.1186/s12887-018-0994-1

Mohr, P. J., Newell, D. B., Taylor, B. N., and Tiesinga, E. (2025). CODATA recommended values of the fundamental physical constants: 2022. *Rev. Mod. Phys.* 97:025002. doi: 10.1103/RevModPhys.97.025002

OIML (2016). OIML R 147: Radiation thermometers - calibration of infrared radiation thermometers / blackbody radiators. Paris, France: International Organization of Legal Metrology (OIML).

Oulasvirta, A., Dayama, N. R., Shiripour, M., John, M., and Karrenbauer, A. (2020). Combinatorial optimization of graphical user interface designs. *Proc. IEEE* 108, 434–464. doi: 10.1109/jproc.2020.2969687

Yoo, S., Lee, K. H., Baek, H., Ryu, B., Chung, E., Kim, K., et al. (2015). Development and user research of a smart bedside station system toward patient-centered healthcare system. *J. Med. Syst.* 39, 1–11. doi: 10.1007/s10916-015-0273-8

Zhao, Y., and Bergmann, J. H. (2023). Non-contact infrared thermometers and thermal scanners for human body temperature monitoring: a systematic review. *Sensors* 23:7439. doi: 10.3390/s23177439