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Comparison Measurements of Infrared Ear Thermometers Against Three Types of Blackbody Sources

S. F. Tsai

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Abstract Body temperature is a basic vital sign of the human body, and the use of infrared ear thermometers for medical diagnosis and health management on human bodies has been widespread nowadays. To gain credibility and confidence in the usage of IR ear thermometers, a standard blackbody source (BBS) with a calibration traceable to ITS-90 is necessitated. Three types of cavity-shaped blackbodies (designated BBC-A, BBC-E, and BBC-J) vertically immersed in a temperature-controlled stirred water bath were developed at the Center for Measurement Standards (CMS) as standard BBSs to calibrate and verify 14 commercial IR ear thermometers produced by six manufacturers. The basic structure of each cavity was designed based on the informative examples recommended in ASTM E-1965, EN 12470-5, and JIS T 4207 standards. The temperature of the blackbody cavity shall be represented by the water temperature near the bottom of the cavity that is measured using an immersed platinum resistance thermometer (PRT) for which the calibration is traceable to our national standard and with an uncertainty no greater than 0.03 °C ($k = 2$). The water bath was evaluated using the PRT to be stable within ±3.5 mK over 1 h and uniform within ±1.1 mK. Three types of BBSs were compared and analyzed utilizing two IR ear thermometers of 0.01 °C resolution as well as the statistical technique of analysis of variance (ANOVA). On the contrary, IR ear thermometers were tested and verified against three BBSs at three blackbody temperatures of 35.5 °C, 37 °C, and 41 °C. The analysis results of ANOVA showed that there is no significant temperature difference among three different structured blackbodies, and the average measured radiance temperature of three BBSs at 35.5 °C, 37 °C, and 41 °C were within 0.026 °C, 0.024 °C, and 0.027 °C of each other. Three among fourteen IR ear thermometers tested were

S. F. Tsai (✉)
Optical Radiation Measurement Laboratory, Center for Measurement Standards,
Hsinchu 30011, Taiwan
e-mail: Shu-Fei_Tsai@itri.org.tw

outside of the 0.2 °C MPE (maximum permissible error) recommended by ASTM E-1965, EN 12470-5, or JIS T 4207 standards while BBC-A and BBC-E were used; however, four were outside of MPE requirement when BBC-J was used.

Keywords ASTM E-1965 · Blackbody source · EN 12470-5 · Infrared ear thermometer · JIS T 4207

1 Introduction

Body temperature regularly monitored by utilizing clinical electrical thermometers, infrared ear thermometers, or forehead thermometers is demanded in schools and assembly places, especially being faced with the worsening global influenza infection nowadays. Among those thermometers, infrared ear thermometers capable of rapid response are designed to measure the ear-canal temperature because the ear canal is located in close proximity to major brain arteries and veins, and its temperature is relatively close to that of the tympanic membrane, which is a recognized measure of core temperature. However, despite their popularity of use, it is essential to provide a means of validating the performance of the IR ear thermometers by being regularly calibrated traceable to the ITS-90 [1] so as to provide reliable information and give confidence to users or clinicians.

Three types of blackbody cavities, designated BBC-A, BBC-E, and BBC-J, were developed and designed to have nearly the same emissivity of unity theoretically to use as standard blackbody sources (BBSs) to verify IR ear thermometers. Their basic structures adopted the examples recommended in ASTM E-1965 [2], EN 12470-5 [3], and JIS T 4207 [4] standards; however, the precise parameters were refined to mutually have comparable emissivity approaching unity. They were compared by two infrared ear thermometers of 0.01 °C resolution, and then all three of them were essential components of standard BBSs to investigate 14 IR ear thermometers as a sample for verifying compliance of the maximum permissible error of a particular type or model of IR thermometer.

Information on the 14 IR ear thermometers being tested is presented in Table 1; however, the manufacturer is designated by code name to avoid business interests. Among them, thermometers with the same code name of manufacturer belong to the same manufacturer and the same model number except that the model number of B-3 is different from that of B-1 and B-2, and the model number of G-2 is different from that of G-1 and G-3. Also, eight of those fourteen thermometers originate from four manufacturers which were selected because each of them has a significant share of the market in Taiwan and the others are well-known foreign products. It will contribute to investigate and characterize the marketed IR ear thermometers in Taiwan as well as to understand the property of famous foreign thermometers.

2 Blackbody Cavities

The main components of BBSs include a blackbody cavity that is a source of thermal radiation, a thermostatic fluid bath, and a reference thermometer that provides the

Table 1 Information on 14 IR ear thermometers being tested in this experiment

Code name of IR ear thermometers	Code name of manufacturer	Domestic product (D) or foreign product (F)	Resolution (°C)
B-1	B	F	0.1
B-2	B	F	0.1
B-3	B[a]	F	0.1
G-1	G	F	0.01
G-2	G[b]	F	0.1
G-3	G	F	0.01
M-1	M	D	0.1
M-2	M	D	0.1
P-1	P	D	0.1
P-2	P	D	0.1
R-1	R	D	0.1
R-2	R	D	0.1
T-1	T	D	0.1
T-2	T	D	0.1

[a] B-1 to B-3 belong to the same manufacturer; however, the model number of B-3 is different from that of B-1 and B-2
[b] G-1 to G-3 belong to the same manufacturer; however, the model number of G-2 is different from that of G-1 and G-3

standard temperature scale. The structural design of blackbody cavities used in this experiment is described as follows.

2.1 BBC-A

A schematic diagram of the blackbody cavity designed by adopting the basic structure of ASTM E-1965 (BBC-A) as shown in Fig. 1 is in the form of a copper cylinder of 55.9 mm diameter and 140 mm length, and with a conical configuration at an angle of 36.4°. The diameter of the cavity aperture is 12 mm, which is large enough for the insertion of all types of the ear thermometers under investigation, and an additional Teflon-made adapter was used for smaller diameter IR ear thermometers to aid in alignment. The same as for the BBC-E and BBC-J described below, the interior surface of the copper cavity was coated with a high emissivity black paint ($\varepsilon = 0.95$) over the 8 μm to 15 μm wavelength range. The effective emissivity of the cavity was evaluated using Gouff'e equation and was found to be better than 0.99988 for an aperture of 12 mm and better than 0.99994 when an adapter was used.

2.2 BBC-E

A schematic diagram of the blackbody cavity designed by adopting the basic structure of EN 12470-5 (BBC-E) is shown in Fig. 2. The cavity is 140 mm long and 50 mm in diameter with a 12 mm diameter aperture. The rear of the cavity is inclined at an

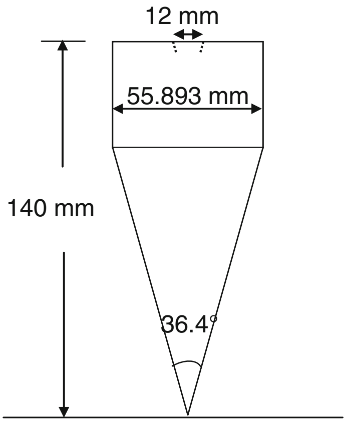

Fig. 1 Schematic diagram of the blackbody cavity (BBC-A) designed by adopting the basic structure of ASTM E-1965

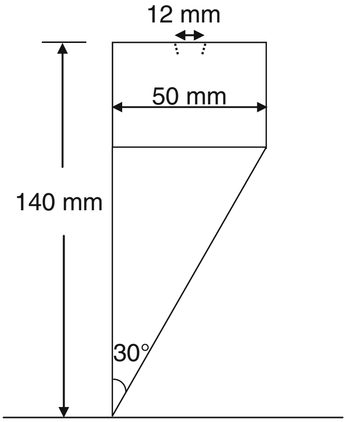

Fig. 2 Schematic diagram of the blackbody cavity (BBC-E) designed adopting the basic structure of EN 12470-5

angle of 30°. The effective emissivity was better than 0.99989 for an aperture of 12 mm and better than 0.99994 when an adapter was used.

2.3 BBC-J

A schematic diagram of the blackbody cavity designed by adopting the basic structure of JIS T 4207 (BBC-J) is shown in Fig. 3. The cavity is 145 mm long and 50 mm in diameter with a 12 mm diameter aperture. The effective emissivity was better than 0.99989 for an aperture of 12 mm and better than 0.99995 when an adapter was used.

3 Results and Discussion

A commercial stirred liquid bath with a 0.01 °C set-point resolution (with 0.00018 °C in the high-resolution mode) provided one cavity at a time with thermostatted conditions, and its access space is 120 × 172 × 457 mm^3. To ensure that the bath was

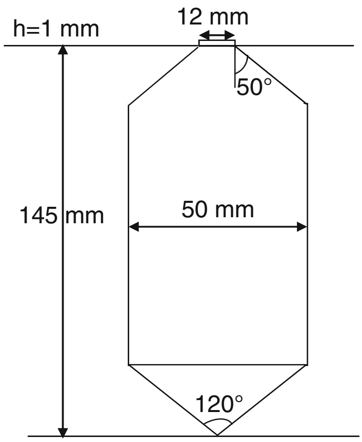

Fig. 3 Schematic diagram of the blackbody cavity (BBC-J) designed adopting the basic structure of JIS T 4207, where the orifice height (*h*) is 1 mm

Table 2 Uniformity and stability evaluation of the bath

Temperature setting (°C)	Radial uniformity (mK)	Axial uniformity (mK)	Stability (mK)
35.5	±0.981	±0.113	±3.5
37	±1.048	±0.187	±2.5
41	±0.709	±0.417	±3.5

isothermal and that the bath temperature was stable during the measuring procedures, its temperature uniformity and stability were evaluated prior to installing the cavity. The radial uniformity was assessed by a calibrated PRT which was placed in the positions of the center and four corners, and the axial uniformity was evaluated at three different depths, within the access space of the bath. The results in Table 2 showed that the bath was uniform to less than ±1.1 mK within the temperature range of 35.5 °C to 41 °C, which meets the required limit of ±0.1 °C of the EN standard. The temperature stability of the bath was measured by monitoring the readout of the PRT for 1 h, and the results of Table 2 and Figs. 4, 5, and 6 showed that the bath was stable to well within ±3.5 mK, which also meets the ±0.2 °C requirements of ASTM, EN, and JIS standards.

Both G-1 and G-3 with a resolution of 0.01 °C were used to compare three cavities, BBC-A, BBC-E, and BBC-J, and the measurements were repeated three times at each blackbody temperature to obtain the average measured radiance temperature of the three BBSs. G-1 and G-3 exhibited good repeatability among the three repeated measurements as shown in Tables 3 and 4, and the radiance temperatures of the three cavities showed a maximum deviation from each other of 0.027 °C when using G-1 or G-3. It is apparent that the average measured radiance temperature compared to BBC-J was higher than the other two, and this conforms to the theoretical prediction since the effective emissivity of BBC-J was the highest among the three on the basis of the calculated emissivity value and Stefan–Boltzmann equation. However, assuming the ambient temperature is 23 °C, the measured maximum difference between the

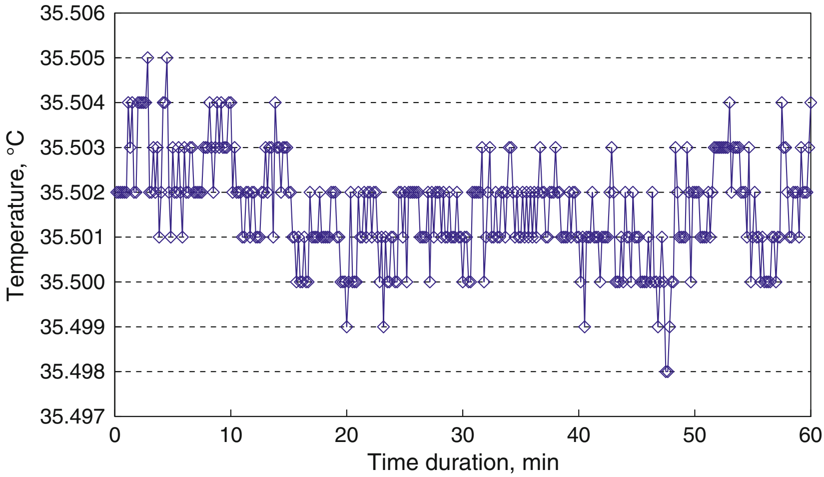

Fig. 4 Stability of the bath over 1 h at 35.5 °C

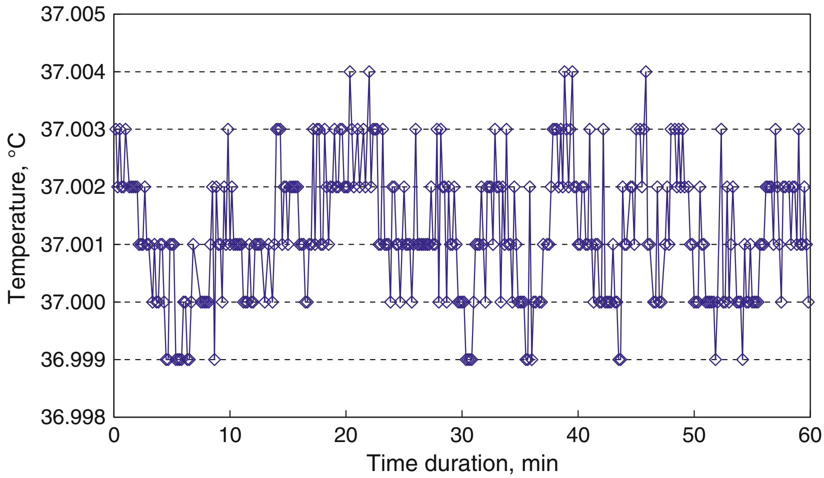

Fig. 5 Stability of the bath over 1 h at 37 °C

three of them was much larger than the theoretical value; furthermore, the thermal radiation generated from BBC-E at 37 °C was not higher than that of BBC-A even though the theoretical emissivity of BBC-E is higher than for BBC-A. These might be caused by the manufacturing tolerance of the cavity, the uncertainty of the predicted emissivity by theory, the aiming point of the ear thermometer, the detection limit of the ear thermometer, and the accuracy of the ear thermometer.

On the other hand, the three BBSs were used to calibrate 14 commercially available IR ear thermometers at 35.5 °C, 37 °C, and 41 °C blackbody temperatures by carefully inserting the device under test (DUT) into the aperture of the blackbody cavity and recording the displayed reading. At each temperature, three measurements were

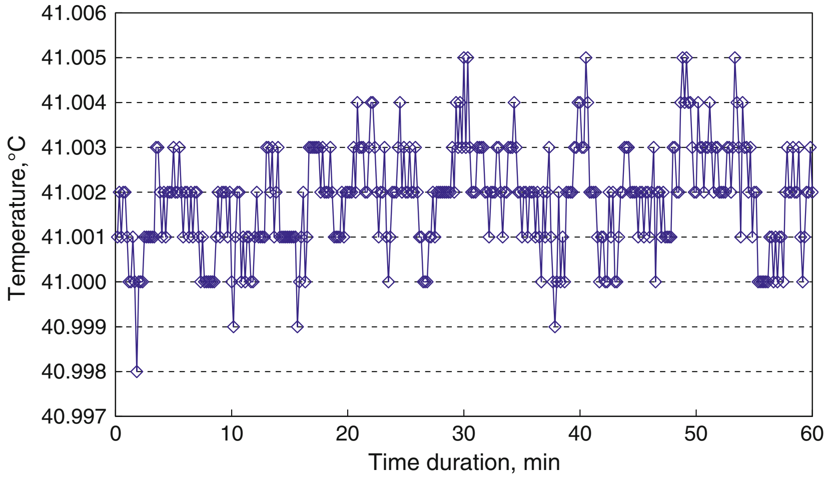

Fig. 6 Stability of the bath over 1 h at 41 °C

Table 3 Radiance temperature of three BBSs measured by G-1, and the theoretical value is obtained assuming the ambient temperature is 23 °C

Temperature setting (°C)	Radiance temperature of BBC-A measured by G-1 (°C)	Radiance temperature of BBC-E measured by G-1 (°C)	Radiance temperature of BBC-J measured by G-1 (°C)	Maximum temperature difference among three sources (°C)	Maximum temperature difference of theoretical value (°C)
Avg					
35.5	35.78	35.79	35.81		
	35.79	35.79	35.82		
	35.79	35.79	35.81		
Avg	35.787	35.790	35.813	0.026	0.000179
37	37.31	37.28	37.31		
	37.29	37.27	37.29		
	37.29	37.28	37.29		
Avg	37.297	37.277	37.297	0.020	0.000199
41	41.26	41.26	41.29		
	41.26	41.28	41.29		
	41.27	41.28	41.29		
Avg	41.263	41.273	41.290	0.027	0.000251

made against each BBS for each individual DUT, and Figs. 7, 8, and 9 represent the average of the three measurements made at each blackbody temperature. It is obvious that R-1 and R-2 always deviated from the reference temperature by a large amount although they were repeatable between each measurement, and G-1 also displayed a high value by about 0.3 °C than the reference temperature even though it showed good repeatability. That is, R-1, R-2, and G-1 were outside of the 0.2 °C MPE when

Table 4 Radiance temperature of three BBSs measured by G-3, and the theoretical value is obtained assuming the ambient temperature is 23°C

Temperature setting (°C)	Radiance temperature of BBC-A measured by G-3 (°C)	Radiance temperature of BBC-E measured by G-3 (°C)	Radiance temperature of BBC-J measured by G-3 (°C)	Maximum temperature difference among three sources (°C)	Maximum temperature difference of theoretical value (°C)
Avg					
35.5	35.44	35.41	35.42		
	35.43	35.40	35.43		
	35.39	35.40	35.42		
Avg	35.420	35.403	35.423	0.020	0.000179
37	36.97	36.98	36.98		
	36.97	36.97	36.99		
	36.95	36.97	36.99		
Avg	36.963	36.973	36.987	0.024	0.000199
41	40.77	40.79	40.80		
	40.76	40.79	40.79		
	40.78	40.78	40.80		
Avg	40.770	40.787	40.797	0.027	0.000251

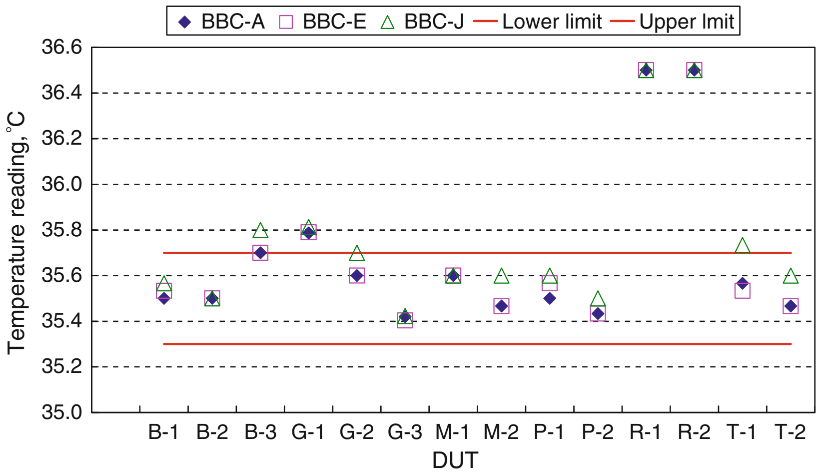

Fig. 7 DUTs were tested against BBS with three cavities at 35.5 °C

BBC-A and BBC-E were used; also, four DUTs including B-3 were outside of the MPE recommended by ASTM E-1965, EN 12470-5, and JIS T 4207 standards when BBC-J was employed.

In addition, via the statistical technique of ANOVA, we would like to know if the mean radiance temperature is the same in our three BBSs, so the readings of 14

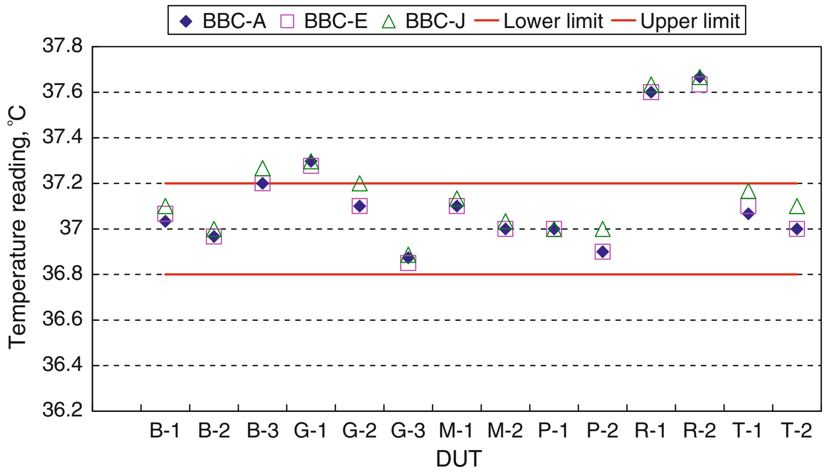

Fig. 8 DUTs were tested against BBS with three cavities at 37 °C

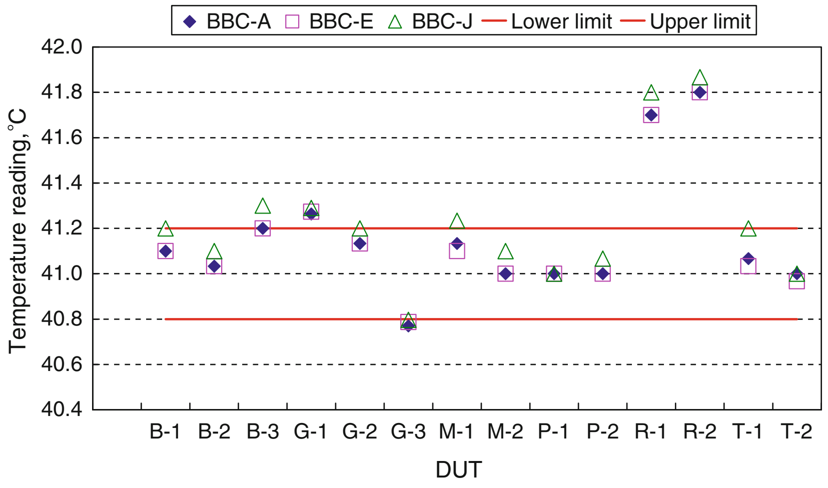

Fig. 9 DUs were tested against BBS with three cavities at 41 °C

DUTs against each of the three BBSs were taken as simple random samples. The null hypothesis in ANOVA is that the means of the groups are equal, i.e.,

$$H_0\colon \mu_1 = \mu_2 = \mu_3$$
$$Ha : \text{not all the means are equal}$$

where μ_1 is the mean number of the radiance temperature in BBS-A, μ_2 is the mean number of the radiance temperature in BBS-E, and μ_3 is the mean number of the radiance temperature in BBS-J.

Table 5 Statistical results of ANOVA to judge whether the mean number of the radiance temperature is the same in our three BBSs

Blackbody temperature (°C)	Source of variation	Sum of squares	Deg. of freedom	Mean squares	F	P value	Critical value F_α
35.5	Between samples	0.036144	2	0.018072	0.14459	0.865839	3.238096
	Within samples	4.874579	39	0.124989			
	Total	4.910723	41				
37	Between samples	0.022348	2	0.011174	0.202446	0.817583	3.238096
	Within samples	2.152567	39	0.055194			
	Total	2.174914	41				
41	Between samples	0.046863	2	0.023432	0.29468	0.746413	3.238096
	Within samples	3.101117	39	0.079516			
	Total	3.147981	41				

Here, the readings of 14 DUTs against each of the three BBSs were taken as simple random samples

The F test is defined as the ratio of mean square between (MSB) to mean square within (MSW), and assuming $\alpha = 0.05$, the F value in Table 5 was less than the critical value F_α whether the radiance temperature is 35.5 °C, 37 °C, or 41 °C. Therefore, since the F statistic is smaller than the critical value, we fail to reject the null hypothesis; in other words, it is apparent that the statistical difference is not significant among the three BBSs, and the differences in these samples are simply due to the different types of DUT used.

4 Conclusions

Three types of BBSs (BBS-A, BBS-E, and BBS-J) with the same reference thermometer, the same thermostatic water bath, but different configurations of cavities designated as BBC-A, BBC-E, and BBC-J, of which the basic structure adopted for each example as recommended in ASTM E-1965, EN 12470-5, and JIS T 4207 standards, have been designed and developed at the CMS. A 25.5 Ω platinum resistance thermometer with an uncertainty no greater than 0.03 °C ($k = 2$) was placed into the water in close proximity to the blackbody cavity to provide a reference temperature traceable to ITS-90. The bath was evaluated to be uniform within ±1.1 mK and stable within ±3.5 mK over 1 h for the temperature range of 35.5 °C to 41 °C, which meet the required uniformity limit of ±0.1 °C as well as the stability limit of ±0.2 °C recommended by the standards mentioned above.

The radiance temperatures of the three BBSs were compared by employing both G-1 and G-3 IR ear thermometers with a resolution of 0.01 °C showed a maximum difference of 0.027 °C among them; however, the thermal radiation generated from BBC-J was, in general, higher than that of the other two just as predicted by theory in light of the highest theoretical emissivity.

ANOVA statistical calculations showed that the differences statistically are not significant among the three BBSs, and the differences in these samples were simply due to different types of IR ear thermometers used.

Eight IR ear thermometers produced by four manufacturers, which represents a significant share of the market in Taiwan, as well as six thermometers originating from well-known foreign manufacturers were chosen as sample DUTs to verify the compliance of the maximum permissible error. Three among fourteen IR ear thermometers tested were outside of the 0.2 °C MPE when BBC-A and BBC-E were used; however, four were outside of the MPE requirement recommended by ASTM E-1965, EN 12470-5, or JIS T 4207 standards when BBC-J was employed.

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