SYNCHRONOUS MEASUREMENTS OF FINGER SURFACE TEMPERATURE FROM THREE DIFFERENT KINDS OF TEMPERATURE SENSORS

Fong-Lin Jang[1] and Chyun-Chau Lin[2]
[1]*Department of Psychiatry, Chi-Mei Medical Center, Tainan, Taiwan*
[2]*Department of Product Design, Shu-Te University, Kaohsiung, Taiwan*
E-mail: frank@stu.edu.tw

ICETI 2012-M2002_SCI
No. 13-CSME-90, E.I.C. Accession 3548

ABSTRACT
The aim of this study was to explore new valid sensors for temperature biofeedback. Three kinds of temperature sensors (thermography imaging, thermistor, and infrared thermopile) were employed to record participants' finger surface temperatures simultaneously. The skin temperature readings resulted in strong correlations between sensors. These results suggested that contact and non-contact temperature sensors all had good synchronous temperature covariance in measuring finger surface temperature.

Keywords: biofeedback; thermistor; infrared thermography; infrared tympanic thermometry.

MESURES SYNCHRONISÉES DE LA TEMPÉRATURE SUR LA SURFACE D'UN DOIGT PAR TROIS DIFFÉRENTS TYPES DE CAPTEURS

RÉSUMÉ
Le but de cette étude est d'explorer de nouveaux capteurs de rétroaction biologique thermique. Ces types de capteurs de température (imagerie thermographique, thermistor, et thermophile infrarouge) ont été employés simultanément pour enregistrer les températures sur la surface du doigt du participant. Lors de la lecture de la température de la peau il y avait une corrélation entre les différents types de capteurs. Les résultats laissent croire que les capteurs avec ou sans contact présentaient tous une bonne synchronisation de la covariance dans la lecture de la température à la surface du doigt.

Mots-clés : rétroaction biologique ; thermistor ; thermographie infrarouge.

1. INTRODUCTION

Biofeedback or muscle relaxation with biofeedback has been one of the major treatment modes in behavior therapy and most widely used in the treatment of psychophysiological and medical disorders [1, 2]. Clinical temperature biofeedback is to measure the neuromuscular and autonomic activity by monitoring the temperature changing of finger surface to reflect the digital blood perfusion and degree of vasoconstriction affected by sympathetic arousal [3]. Reduced digital microcirculation secondary to sympathetic reflex response can be reflected by a transient decrease in surface temperature. When compared with the sophisticated and complex analyses of digital flux and pulse volume, finger surface temperature is easy and simple to analyze [4].

The contact sensor of the thermistor is used in traditional temperature biofeedback. The thermistor sensor is fixed to the finger by a tape or a strap [3]; this method has been applied for more than three decades [5]. The sensor has limited portability and requires equilibration time before a stable reading is achieved [6]. The literature regarding the method of fixing the probe is scanty, and states just to tape the probe gently [3] or comfortably [7]. Some authors have emphasized that the tape should be wrapped around the finger at an angle rather than like a ring so as to reduce the possibility of restricting blood flow [8]. Regarding the locus of the fixed temperature sensor, the fingertip is most favored because the temperature variation there is more pronounced than at other sites on the finger [4]. But the dorsum of the finger has also been recommended, when considering postural comfort during temperature monitoring. No single locus is standard, nor has any particular locus been superior to another [3, 9]. Up to now, there is no standard instrumentation for traditional temperature biofeedback.

In recent years, infrared imaging technology has been applied for everything from military to medical purposes in which there is a vascular component [10]. Infrared thermography can survey the surface temperature quickly and accurately. The radiance between an object and the receptor of the thermography system does not diminish with the distance in the absence of scattering and absorption [11, 12]. So the receptor needs no contact with the skin, and the probable imperfection of impeding local circulation in the process of taping the sensor, like the traditional temperature biofeedback machine, does not exist. A study on body temperature changes in sleep has demonstrated strong correlation between the thermistor and infrared thermal imaging in synchronous measuring of finger surface temperature [13].

Another kind of temperature sensor is the one used in the infrared tympanic thermometer. It is a non-contact sensor that provides fast and accurate measurement of core temperature, and the reliability and validity of its use have been well established [14, 15]. There have also been studies on the use of the infrared tympanic thermometer to monitor finger skin temperature, and the correlations with other kinds of temperature sensors in such measuring were strong [6, 16, 17].

The purpose of this study was to synchronously compare the finger surface temperature readings from three different kinds of temperature sensors in a setting simulating clinical relaxation therapy. We aimed to verify whether the temperature readings from these three sensors all had the same covariation in the process of temperature monitoring.

2. METHODS

2.1. Participants

Sixteen healthy volunteers, ten males and six females (23.1±2.0 years old) were recruited. All gave informed consent. None of the subjects had a recent history of fever, heat-illness or intolerance, vascular disease, or serious injury to the hand or fingers. All subjects were non-smokers and in good physical condition. The subjects refrained from alcohol, caffeine-containing drinks, and tobacco for at least two hours prior to the experiment.

Table 1. Physical characters of three different kinds of temperature sensors.

	Thermistor (AT-42)	Thermography (TVS-600)	Thermopile (10TP583T)
Temperature range	0–45°C	–20–150°C	–20–100°C
Resolution	0.01°C	0.1°C	0.1°C
Recording interval	0.25 seconds	10 seconds	0.015 seconds

2.2. Experimental Devices and Procedures

Three kinds of devices to measure finger surface temperature were used: (1) traditional temperature biofeedback (AT-42 of Stoelting Co., USA) with a thermistor sensor; (2) an infrared thermography camera (TVS-600 of Avionics Co., Japan); and (3) a designed ring with an infrared thermopile sensor for automatic and continuous measurements (10TP583T of Semitec Co., Japan) (Table 1).

The temperature at the tip of the left middle finger was measured by traditional temperature biofeedback (AT-42) with the thermistor sensor gently taped. The temperature at the tip of the right middle finger was measured by infrared thermography camera (TVS-600). To measure a fixed locus of surface temperature from thermography imaging, a piece of curved bamboo with a hole 3 mm in diameter was taped gently to the fingertip of the right middle finger, and the temperature readings came from the hole in the bamboo (Fig. 1). The designed ring, using an infrared thermopile sensor (10TP583T), was used to measure the surface temperature of the dorsal side of the proximal phalange of the left middle finger. Attached to the designed ring was an elastic band of alloy. The metal band could be curled around the finger so that the body of the device is fixed on the finger lightly and stably. The thermopile sensor was placed at the edge of the device body, and the distance between the skin of the finger and the sensor was about 2.5 mm. A USB cable connected the ring with a computer, and through software, the temperature readings of the thermopile could be transmitted to the computer and seen on the monitor.

The environmental temperature in the laboratory during the experiment was from 25 to 27°C and humidity was from 50 to 60%. The subjects were seated in a comfortable armed sofa. They rested for 2–10 minutes until the temperature reading of each sensor became stable. Then, the subjects practiced cognitive imagery muscle relaxation by listening to an audiotape.

During the process of muscle relaxation, three different kinds of temperature sensors were continuously measuring the surface temperature from the three loci of the fingers. The temperature readings from the different sensors were displayed digitally and were videotaped synchronically by 3 cameras. All of the video data from the cameras were transmitted to computer via a digital signal processing card (VG4C-XP of Chateau Technical Corp., Taiwan) and were converged to video files for further inspection (Fig. 1). The temperature data were selected every half a minute and totally for 14 minutes from a fixed middle section of the muscle relaxation procedure to show the outline of the temperature variation during the process of relaxation.

2.3. Statistical Analysis

The data were analyzed using linear regression to measure the strength of the relationship between measurements made by the AT-42 thermistor, the infrared thermography camera, and the thermopile sensor ring.

3. RESULTS

Twenty-eight temperature signals for each device from 16 subjects were used for statistical analyses. The temperature data were analyzed with simple linear regression to measure the relative strength between measurements made by (1) the AT-42 thermistor (as the independent variable) and the TVS-600 infrared ther-

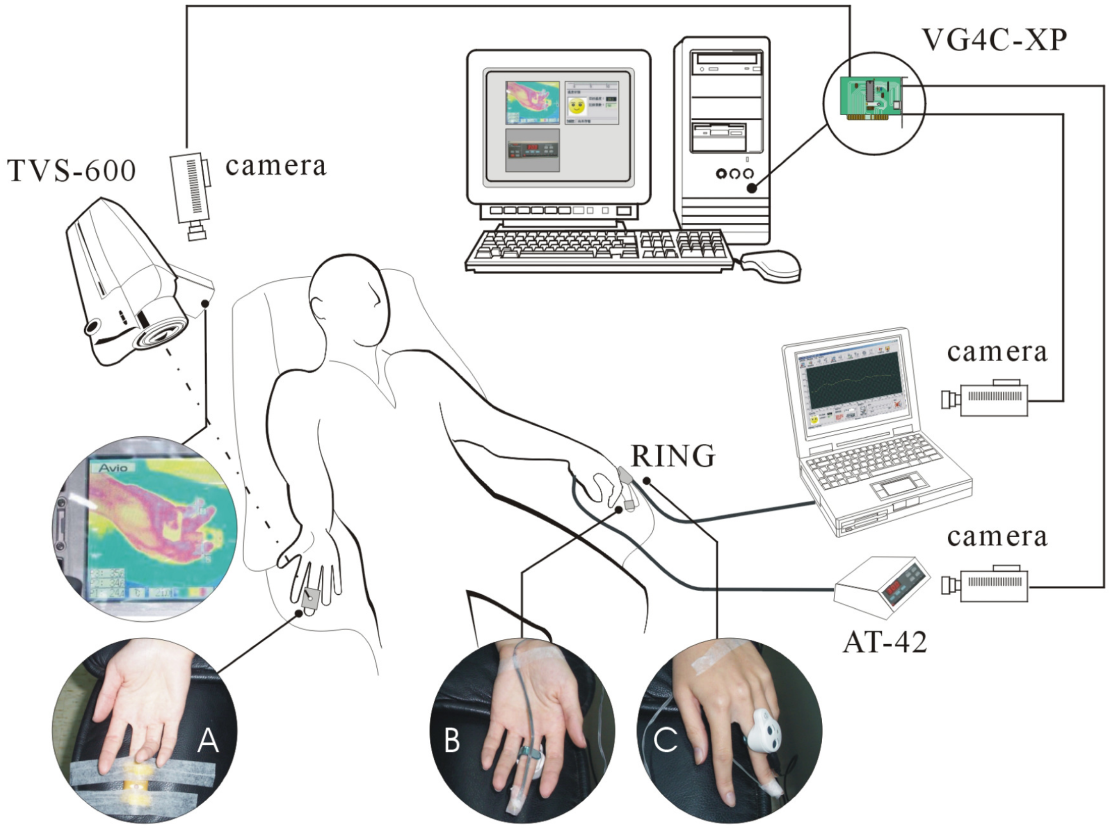

Fig. 1. The setups of three kinds of devices for measuring finger surface temperatures. A piece of curved bamboo with a 3 mm hole as a fixed locus for TVS-600 is shown in A; setups of AT-42 and the Thermopile Ring are shown in B and C.

mography camera (as the dependent variable); (2) the TVS-600 infrared thermography camera (as the independent variable) and the thermopile sensor ring (as the dependent variable); and (3) the AT-42 thermistor (as the independent variable) and the thermopile sensor ring (as the dependent variable).

Twenty-eight means of skin temperature measurements from each sensor (Table 2) resulted in overall correlation coefficients of $R = 0.98$ ($p < 0.001$) between thermistor and thermography imaging sensors, $R = 0.95$ ($p < 0.001$) between thermography imaging and infrared thermopile sensors, and $R = 0.96$ ($p < 0.001$) between thermistor and infrared thermopile sensors. Regression analyses for most participants resulted in strong correlations between two sensors; 45 coefficients were between 0.98 and 0.67, $p < 0.001$. Only three coefficients ($R = 0.53$, 0.60, and 0.64, $p < 0.005$) were less than 0.65 and still correlated (Table 3).

4. DISCUSSIONS

The results showed that the correlation of relative temperature changes from contact or non-contact temperature sensors at different loci of both hands were high ($R = 0.95$–0.98 for overall means, and $R = 0.98$–0.67 for most individual measurements, $p < 0.001$). These results supported the notion that the relative changes of temperature are parallel during the process of relaxation, and that no particular locus is standard or superior [3]. In Heuvel et al.'s study [13], infrared thermal images were taken every 30 seconds and thermistor measures were acquired every second. The thermistor measures were integrated over a 30-second period and synchronized to infrared thermal images in a time discrepancy within ± 1 second. But in our study, with

Table 2. Means and standard deviations (sd) of different temperature devices ($n = 16$).

	TVS600		AT42		RING	
Epoch index	mean	sd	mean	sd	mean	sd
1	31.4	2.3	31.0	2.8	30.9	1.3
2	31.6	2.3	31.1	2.9	31.0	1.3
3	31.8	2.5	31.2	2.9	31.1	1.4
4	32.0	2.6	31.5	3.0	31.1	1.4
5	32.0	2.7	31.7	3.1	31.2	1.5
6	32.2	2.6	31.8	3.1	31.3	1.5
7	32.2	2.8	32.0	3.1	31.3	1.5
8	32.5	2.8	32.0	3.1	31.4	1.6
9	32.4	2.8	32.0	3.1	31.5	1.6
10	32.5	2.9	32.2	3.1	31.6	1.7
11	32.8	2.9	32.3	3.1	31.7	1.7
12	32.8	3.1	32.4	3.1	31.8	1.8
13	32.9	3.0	32.5	3.1	31.9	1.8
14	33.0	3.0	32.5	3.0	31.9	1.8
15	32.8	3.1	32.5	3.0	31.9	1.8
16	32.9	3.0	32.5	2.9	31.9	1.8
17	32.9	2.9	32.6	2.7	31.9	1.8
18	32.9	2.9	32.6	2.7	32.0	1.8
19	32.8	2.9	32.6	2.7	32.0	1.7
20	32.8	2.8	32.7	2.6	32.0	1.6
21	32.9	2.7	32.7	2.6	32.1	1.6
22	33.0	2.7	32.8	2.6	32.2	1.6
23	33.0	2.8	32.8	2.7	32.2	1.6
24	33.0	2.8	32.8	2.7	32.3	1.6
25	33.1	2.8	32.7	2.7	32.3	1.6
26	33.1	2.8	32.8	2.7	32.3	1.6
27	33.0	2.9	32.8	2.7	32.3	1.6
28	33.0	2.9	32.7	2.7	32.4	1.6

the help of video cards and cameras, we could continuously measure skin surface temperature at different loci from different devices and record the instantaneous readings synchronously.

With the contact temperature thermistor sensor used in traditional temperature biofeedback, it is essential to keep the sensor in constant and appropriate contact with the skin. However, there is no data in the literature regarding the standard and appropriate procedure for fixing a thermistor probe. In this study, we taped the sensor onto two spots: the fingertip for the thermistor probe and the palm for the cable, like fixing an IV line. It was thought that fixing the cable at the palm rather than at the phalange of the same finger would be less of a hindrance to local circulation in the finger.

The results of this article supported the use of thermography as a good non-contact instrument to assess skin surface temperature and as one that can quantify relative changes in temperature as accurately as the contact methods of thermometry [13]. However, the key issue of thermography is how to localize the fixed monitored area in images. In this study, a piece of semicircular bamboo was gently taped to a finger, with no worry about slippage of the bamboo or interference in digital local circulation. The hole in the bamboo made it easier to uncover the fixed area to be measured. We recommend the use of a piece of bamboo, wood, or plastic with a hole in it in thermography to continuously measure skin surface temperature over a fixed area.

Table 3. Regression analyses for 16 subjects, with gender (m = male, f = female), coefficient (R), and significance (p). $^{*}p < 0.005$, $^{**}p < 0.001$.

Gender	Subject code	AT42 – TVS600		TVS600 – RING		AT42 – RING	
		R	p	R	p	R	p
m	1	0.81**	0.000	0.80**	0.000	0.98**	0.000
f	2	0.81**	0.000	0.82**	0.000	0.96**	0.000
m	3	0.84**	0.000	0.93**	0.000	0.81**	0.000
m	4	0.94**	0.000	0.84**	0.000	0.89**	0.000
m	5	0.82**	0.000	0.96**	0.000	0.76**	0.000
m	6	0.84**	0.000	0.94**	0.000	0.77**	0.000
f	7	0.74**	0.000	0.64**	0.000	0.69**	0.000
f	8	0.92**	0.000	0.85**	0.000	0.90**	0.000
m	9	0.67**	0.000	0.53*	0.004	0.70**	0.000
m	10	0.89**	0.000	0.82**	0.000	0.92**	0.000
f	11	0.73**	0.000	0.60**	0.001	0.94**	0.000
f	12	0.86**	0.000	0.82**	0.000	0.86**	0.000
m	13	0.91**	0.000	0.90**	0.000	0.80**	0.000
m	14	0.91**	0.000	0.91**	0.000	0.86**	0.000
m	15	0.83**	0.000	0.93**	0.000	0.76**	0.000
f	16	0.89**	0.000	0.90**	0.000	0.95**	0.000

The thermopile sensor utilized in the infrared tympanic thermometer also had strong correlations with other kinds of sensor in measuring finger surface temperature. In previous studies, the infrared tympanic thermometer was held by the hand, and the distances between the infrared temperature sensor and the finger surface were 1–2 cm [18] or 1–5 mm [19]. In this study, the distance was about 2.5 mm. The advantage of implanting the sensor in the body of the designed ring is that the sensor could continuously monitor one fixed locus and maintain a constant measuring distance from the locus of finger surface to the sensor.

5. CONCLUSIONS

The study proposes and compares the instrumentation of three kinds of temperature sensors at different loci of both hands to measure finger surface temperature. Using cameras and a video card system, it is possible to record the temperature readings from different sensors instantaneously and synchronically. The sensors used in this study displayed good mutual correlation in the process of practicing muscle relaxation.

REFERENCES

1. Futterman, A.D. and Shapiro, D., "A review of biofeedback for mental disorders", *Hospital and Community Psychiatry*, Vol. 37, No. 1, pp. 27–33, 1986.
2. Schwartz, M.S. and Olson, R.P., "A historical perspective on the field of biofeedback and applied psychophysiology", in M.S. Schwartz and F. Andrasik (Eds.), *Biofeedback: A Practitioner's Guide*, 3rd edn., pp. 3–19, Guilford Press, 2003.
3. Peek, C.J., "A primer of biofeedback instrumentation", in M.S. Schwartz and F. Andrasik (Eds.), *Biofeedback: A Practitioner's Guide*, 3rd edn., pp. 43–87, Guilford Press, 2003.
4. Kistler, A., Mariauzouls, C. and van Berlepsch, K., "Fingertip temperature as an indicator for sympathetic responses", *International Journal of Psychophysiology*, Vol. 29, No. 1, pp. 35–41, 1998.
5. Sargent, J.D., Green, E.E. and Walteres, E.D., "The use of autogenic feedback training in a pilot study of migraine and tension headaches", *Headache*, Vol. 12, No. 3, pp. 120–124, 1972.
6. Burnham, R.S., McKinley, R.S. and Vincent, D.D., "Three types of skin-surface thermometers: a comparison of reliability, validity, and responsiveness", *American Journal of Physical Medicine and Rehabilitation*, Vol. 85,

No. 7, pp. 553–558, 2006.
7. Danskin, D.G. and Crow, M.A., *Biofeedback: An Introduction and Guide*, pp. 22–37, Mayfield, 1981.
8. Garder, K.R. and Montgomery, P.S. (Eds.), *Clinical Biofeedback: A Procedural Manual*, pp. 177–191, The Williams and Wilkins Company, 1977.
9. Duckro, P.N., Schultz, K. and Shaffer, F., "Comparability of skin temperatures from three sites on the hand", *Biofeedback and Self-Regulation*, Vol. 11, No. 4, pp. 293–298, 1986.
10. Head, J.F. and Elliott, R.L., "Infrared imaging: Making progress in fulfilling its medical promise", *IEEE Transactions on Medical Imaging*, Vol. 21, No. 6, pp. 80–85, 2002.
11. Jones, B.F., "A reappraisal of the use of infrared thermal image analysis in medicine", *IEEE Transactions on Medical Imaging*, Vol. 17, No. 6, pp. 1019–1027, 1998.
12. Jones, B.F. and Plassmann, P., "Digital infrared thermal imaging of human skin", *IEEE Engineering in Medicine and Biology Magazine*, Vol. 21, No. 6, pp. 41–48, 2002.
13. Heuvel, C.J. van den, Ferguson, S.A., Dawson, D. and Gilbert, S.S., "Comparison of digital infrared thermal imaging (DITI) with contact thermometry: Pilot data from a sleep research laboratory", *Physiological Measurement*, Vol. 24, pp. 717–725, 2003.
14. Childs, C., Harrison, R. and Hodkinson, C., "Tympanic membrane temperature as a measure of core temperature", *Archives of Disease in Childhood*, Vol. 80, pp. 262–266, 1999.
15. Shinozaki, T., Deane, R. and Perkins, F.M., "Infrared tympanic thermometer: Evaluation of a new clinical thermometer", *Critical Care Medicine*, Vol. 16, No. 2, pp. 148–150, 1988.
16. Kayikcioglu, A., "Two practical devices for monitoring temperature", *Plastic and Reconstructive Surgery*, Vol. 111, No. 5, pp. 1778–1779, 2003.
17. Matsukawa, T., Ozaki, M., Nishiyama, T., Imamura, M. and Kumazawa, T., "Comparison of infrared thermometer with thermocouple for monitoring skin temperature", *Critical Care Medicine*, Vol. 28, No. 2, pp. 532–536, 2000.
18. Hershler, C., Conine, T.A., Nunn, A. and Hannay, M., "Assessment of an infra-red non-contact sensor for routine skin temperature monitoring: A preliminary study", *Journal of Medical Engineering and Technology*, Vol. 16, No. 3, pp. 117–122, 1992.
19. Bird, H.A., Calguneri, M., Leatham, P.A. and Wright, V., "Measurement of temperature in the arthritic hand", *Rheumatology and Rehabilitation*, Vol. 19, No. 4, pp. 205–211, 1980.