Where Should Core Temperature Be Measured in Human Experiments?

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Abstract

The site of noninvasive measurement of core temperature in human subjects should be selected in order to obtain accurate thermal information for the purpose of the experiments: average deep body temperature or thermal information regarding the central thermoregulatory mechanism.

Esophageal temperature (Tes) has been preferably measured for average deep body temperature, since it mirrors closely central blood temperature.

Rectal temperature (Tre) renders stable data in a steady state, not being influenced by the outer thermal environment or by shell temperature, but is not appropriate at least in experiments where rapid changes in body temperature are expected, since it is unable to follow relatively rapid changes in blood temperature.

Tympanic temperature (Tty) has been measured as an indicator of brain temperature, which is considered to provide the major thermal input to the integrative center for thermoregulation. Intracranial temperature parallels Tty, while their changes are often preceded by those in Tes.

The right and left Tty's are not always equal exactly, but may even change in opposite directions in many occasions where uneven blood flow occurs between the cerebral hemispheres, including unilateral cerebrovascular disorders. Regional or unilateral impairment of the balance between heat production in the brain and heat dissipation from it may elicit unevenness or asymmetry in the brain temperature which is reflected in the bilateral Tty's.

Measurement of Tty is safe and causes no discomfort, if maneuvered properly. Measurement of aural canal temperature or infrared tympanic thermometry cannot substitute the direct measurement of Tty.

Thermoregulatory responses are better correlated with Tty than Tes or other trunk temperatures.

Key words core temperature, tympanic temperature, esophageal temperature, thermometry, thermoregulation

Introduction

Core temperature is defined as deep body temperature but is not at all uniform: the temperature of an organ with a relatively high metabolic rate is higher than that of arterial blood perfusing it, such as the liver, brain, kidney, etc. Moreover, in the human subject, noninvasive measurements of deep body temperature can be done only at limited

sites, such as the axilla, oral cavity, rectum, vagina, esophagus, tympanic membrane, nasopharynx and urinary bladder. Techniques of body temperature measurements, especially for clinical use, have been comprehensively reviewed by Togawa (1985).

Nevertheless, accurate thermal information is often required, especially in the laboratory, where rectal, oral, esophageal

and tympanic temperatures are most commonly measured. The sites of measurement should be selected according to the purpose. In the present article, advantages and disadvantages of the measurement of those temperatures as an indicator of core temperature will be appraised.

Many kinds of temperature sensors are available currently, but thermistors and thermocouples are preferably used in most laboratories of thermal physiology.

Validity as an Indicator of Average Deep Body Temperature

In the laboratory, core temperature is measured to obtain either average deep body temperature or major thermal information regarding the central thermoregulatory mechanism. For the former purpose, esophageal temperature (Tes) has been preferably measured, since it mirrors closely the blood temperature of the pulmonary artery or aorta, where the blood has returned from and is to be distributed to organs and tissues, and follows rapidly changes in the blood temperature, with time constant of approximately 1 min (Gibson et al., 1981; Shiraki et al., 1986; Sawka and Wenger, 1996).

Rectal temperature (Tre) was once most commonly measured in many laboratories since it renders far more stable data, especially in a prolonged monitoring, compared to axillary (Tax) or oral temperature (Tor). The measured value was considered reliable, not being influenced by the outer thermal environment or by shell temperature, and has been demonstrated to be higher than that measured at any other site (except for urinary bladder temperature which has been reported to be an average of 0.04°C higher than Tre: Ilsley et al., 1983). Tre has been shown to be an average of 0.23°C higher than pulmonary arterial temperature (Eichna et al., 1951; Ilsley et al., 1983), 0.22°C higher than right ventricular temperature (Eichna et al., 1951), and 0.24°C higher than Tes in normothermic subjects (Cranston et al., 1954).

However, it was repeatedly demonstrated in the 1950's that Tre was unable to follow relatively rapid changes in blood temperature (Cranston et al., 1954; Cooper & Kenyon, 1957; Carlsten & Grimby, 1958). Many investigators have been reluctant to measure Tre as an indicator of body temperature at least in experiments where rapid changes in core temperature are expected, such as experiments where a sudden change in thermal load or when exercise is involved. However, in a steady state, Tre can be an appropriate index of core temperature to estimate body core heat storage.

Tor level is close to Tes level, if carefully measured. It changes in parallel better with Tes than Tre in response to changes in air temperature, but is less closely related to Tes than Tre during work-load variations (Mairiaux et al., 1983), and its measurement is less practical, since the mouth has to be kept closed; if the mouth is opened to breathe or to drink, time is needed for Tor to stabilize.

Validity as an Indicator of Regulatory Temperature

On the other hand, tympanic temperature (Tty) has been measured as an indicator of brain temperature, especially hypothalamic temperature, which is considered to provide the major thermal input to the integrative center for thermoregulation. It offers a more precise thermal information for thermoregulation than Tes, since thermoregulatory responses are better correlated with Tty than Tes, which will be discussed in a later section.

Since Benzinger (1959) and Benzinger and Taylor (1963) proposed the measurement of Tty as an approximation of brain temperature, it has been evidenced by many investigators that Tty reflects brain temperature with considerable precision. In animal experiments, Tty has been shown to fluctuate in the same manner as hypothalamic temperature (Tanabe and Takaori, 1954; Baker et al., 1972). In humans also, Tty has been observed to parallel intracranial temperatures

recorded after craniotomy (Soutsu, 1991; Mariak et al., 1994; Ogawa et al., 1995). While Soutsu's measurements on 9 cases shows Tty being lower than the temperature of the cerebral parenchyma (including cistern, ventricle and tumor cavity) by 0.37°C on average ($0-0.9^{\circ}\text{C}$) and than the cerebral surface by 0.12°C on average ($0-0.2^{\circ}\text{C}$), Mariak's data on 11 patients indicate that Tty exceeded epidural temperature by a mean of 0.2°C and was nearly equal to subdural temperature. We carried out postcraniotomy thermometry in 9 cases, and Tty was lower than the intraparenchymal temperature by $0-0.25^{\circ}\text{C}$ but was higher than Tes by $0-0.3^{\circ}\text{C}$ (Fig. 1A), except for one case. In that case, a good size of cerebral tumor (glioblastoma) was excised and the temperature in the cavity produced by the excision was lower than Tty as well as

Fig. 1. Simultaneous recordings of the temperature of the tumor cavity, tympanic temperatures, and esophageal temperature following excision of metastatic adenocarcinoma in the left cerebral hemisphere (A), and glioblastoma in the right hemisphere (B) (Ogawa et al., 1995).

Tes (Fig. 1B) (Ogawa et al., 1995).

The validity of Tty measurement as an index of brain temperature has been disputed by some investigators on the basis that Tty fails to follow changes in central blood temperature as rapidly as Tes, and that Tty is considerably 'contaminated' by the ambient and head skin temperatures (Nadel and

Horvath, 1970; Shiraki et al., 1986, 1988; Brengelmann, 1987). It should be noted however that, while fluctuations of Tty tended to be preceded by Tes, it is well synchronized with those of brain and ventricular temperatures (Fig. 1). Furthermore, Tty values reported by some of those authors were significantly lower than Tes even in normothermia.

The brain is an organ with a high metabolic rate, producing considerable heat, and brain temperature in general is higher than arterial temperature. Consequently, the brain is cooled by circulatory convection and conduction to tissues in the vicinity. It should be natural therefore that, at least in normothermia, Tty reflects well brain temperature that maintains a higher value than Tes representing aortic temperature. Brinell and Cabanac (1989) noted that Tty is maintained at 0.1°C above Tes at rest in normothermia, and is virtually unaffected by ambient temperature as low as 0°C .

An increase in cerebral blood flow without a significant change in brain metabolic rate induces a decrease in brain temperature, which is reflected on Tty. Intravenous administration of acetazolamide, which is known to increase cerebral blood flow, was followed by a consistent decrease of Tty in

Fig. 2. Records showing the effect of acetazolamide administration on tympanic temperature recorded bilaterally in two subjects Ogawa et al., 1995; Sugino et al., 1997).

healthy subjects (Fig. 2) (Sugino et al., 1997).

During hyperthermia, however, Tty may be lower than Tes. It has been demonstrated that the brain is selectively cooled in hyperthermia and thus protected from hyperthermic damage in many mammals and birds. It has been inferred that selective brain cooling takes place also in humans by means of a counter-current heat exchange mechanism between cerebral arterial blood and cool venous blood from the scalp and face (Cabanac and Caputa, 1979a; Cabanac and Brinnel, 1985; Nagasaka et al., 1990), although there are some disputes on its existence (Deklunder et al., 1991; Jessen and Kuhnen, 1992). Nevertheless, evidence for its existence has been accumulated lately, as will be discussed in a later section.

The right and left Tty's are not exactly equal but there is frequently a difference of up to 0.05°C between them (Ogawa et al., 1992) (see Fig. 3). Furthermore, they may occasionally change in directions opposite to each other. Brain temperature is determined by the balance between heat production by cerebral metabolism and heat loss due to circulatory convection and conduction to the surroundings; impairment of this balance may result in unevenness or asymmetries in the brain temperature which are reflected in the bilateral difference in Tty (Ogawa, 1994;

Fig. 3. Continuous 48-hr recording of the right and left tympanic temperatures by the use of thermistor probes with soft coil spring (Ogawa et al., 1994).

Ogawa et al., 1995).

The right and left Tty's may change in

different directions when the body or head is tilted to one side accompanied by bilateral asymmetry in the blood flow of the brain hemisphere (Ogawa et al., 1993a). Stellate ganglion block causes a slight (0.04–0.1°C) but significant fall in the ipsilateral Tty, together with an increase in cerebral blood flow on the ipsilateral side (Umeyama et al., 1993). Compression of the skin area of the neck over the right or left carotid artery results in an increase in ipsilateral Tty (Ogawa et al., 1993b). A significant bilateral difference in Tty's is observed in patients with unilateral cerebrovascular disorders, the Tty being lower on the side where brain has been damaged. The extent of the brain damage correlates well with the degree of the bilateral difference in Tty (Nishita, 1992).

Nasopharyngeal temperature has been claimed to follow Tty considerably precisely, being within 0.05°C of the latter (Benzinger and Taylor, 1963). A probe can be inserted during local or general anesthesia and has been used by some clinicians. The validity has been questioned however, since the temperature fluctuates by the passage of gases and influenced the temperature of the inspired air, and the probe is easily displaced (Vale, 1981).

Technical Problems

In measurements of either Tre, Tes or Tty, careful sterilization of the probe is required, since it touches delicate tissue.

Tre is commonly measured by a probe inserted deeper than 7 cm from the anal sphincter, but the temperature with a probe inserted as deep as 20 cm is often lower than that measured at a shallower site as much as 0.8°C (Mead and Bonmario, 1949).

A probe for Tes measurement is inserted into the esophagus without much difficulty in general but often requires surface anesthesia of the nasopharynx, especially in a nervous subject. The temperature in the esophagus is not uniform along its length (Whitby and Dunkin, 1968). The temperature in the upper part of the esophagus has been demonstrated to be influenced by tracheal air (Cranston et

al., 1954). The probe should be inserted until it is approximately 40 cm from the nostril or 24-28 cm below the corniculate cartilages, to reach the level of the heart.

Not only clinicians but also many experimental investigators have often been reluctant to measure Tty due to technical difficulty, frequent pain and the risk of injuring or perforating the tympanic membrane (Webb, 1973; Wallace et al., 1974; Davis et al., 1981; Tabor et al., 1981).

As a substitute of Tty, the temperature of the air within the external auditory meatus or of its wall has often been measured, because the placement of the probe is much easier and safer, and values have been reported to parallel Tes (Webb, 1973). However, the values are much lower than Tty and are affected by ambient temperature, showing a considerable temperature gradient along the ear canal (Cooper et al., 1964; Gibbons, 1967; Greenleaf and Castle, 1972; Marcus, 1973; Sharkey et al., 1987). Confusion has arisen as the validity of Tty has often been criticized on the basis of the data on auditory canal temperature. Most data with Tty lower than Tes as measured in a temperate or cooler environment has been caused by a technical error of the sensor not being placed on the tympanic membrane but on the canal wall.

The use of an infrared tympanic thermometer is convenient and gives data highly correlated with those obtained using a thermometer in contact with the tympanic membrane (Hirata et al., 1990; Jakobsson et al., 1992). However, there is an individual variation in the slope and the position of the y-intercept of the regression line, and the value is affected by the ambient temperature (Hirata et al., 1990).

The disadvantages with Tty measurement have been eliminated by the use of a probe that softly touches the tympanic membrane (Dickey et al., 1970; Masuda and Uchino, 1978). A thermistor equipped with a soft coil spring devised by Masuda and Uchino can be placed on the eardrum with little or no pain, and its correct positioning can be

judged by the subject being able to hear a loud scratching sound. The most accurate measurement of Tty can be made by placing the probe on the lower anterior quarter of the tympanic membrane, where blood is supplied from a branch of the internal carotid artery (Brinnel and Cabanac, 1989). This part is located in the deepest end of the external auditory meatus and the thermistor with soft spring usually slides to reach that portion automatically, as the trace can be ascertained otoscopically after the removal of the probe. The auditory canal should be plugged for accurate measurement avoiding direct thermal interference from the environment. After the fixation of the probe, no noxious sensation is experienced, even during vigorous exercise. In fact, we have recorded Tty using a portable logger continuously for a prolonged period as long as 48 hr without the subjects suffering discomfort (Ogawa et al., 1992) (Fig. 3). A mild disturbance in hearing caused no inconvenience in the activities of daily life.

Correlations of Thermoregulatory Responses with Measured Temperatures

Various nonthermal stimuli which are considered to affect central thermoregulatory activity cause increases or decreases in sweat rate, which in turn result in falls or rises of core temperatures, respectively, including Tty and Tes. For example, inhalation of 5-6% carbon dioxide induces an increase in sweat rate, followed by a drop in the core temperatures (Sugenoya and Ogawa, 1985). Hyperventilation causes the opposite responses. In humans, infusion of thyrotropin-releasing hormone induces an increase in sweat rate and a drop in the core temperatures (Sugenoya et al., 1988). Alcohol intake initially causes a transient increase in sweat rate and a drop in the core temperatures. Thermal dehydration results in a decrease of sweat rate and an elevation of body temperature. Hemodialysis exerts the reverse effects (Ogawa and Asayama, 1987). In such occasions, Changes in Tty mirrors those in Tes after a slight delay.

In other occasions, where the brain is selectively cooled, Tty may not parallel Tes, while thermoregulatory responses corresponds well with a fall of Tty. For example, in a warm environment where thermal sweating is present, facial cooling causes a fall in Tty and a rise in Tes, accompanied by a sustained decrease in sweat rate (Cabanac and Caputa, 1979b; McCaffrey et al., 1975). When the face is fanned or blown on from the side, Tty on the ipsilateral side decreases more than that on the contralateral side, and the sweat rate on the ipsilateral forearm often decreases slightly more than that on the contralateral side, while Tes hardly changes (Cabanac et al., 1987; Ogawa et al., 1989b). Thus selective brain cooling results in a depression of heat dissipating responses and often a rise in the temperature of other organs with the exception of the brain. More direct cooling of the carotid artery by cooling a circumscribed unilateral area of the neck also causes a fall of Tty on the same side, while Tty of the other side, as well as Tes, often elevates, and the forearm sweating rate on the ipsilateral side usually lowers compared to that on the contralateral

Fig. 4. Effects of ventilation of a circumscribed right-side area of the neck upon the right and left tympanic temperatures, esophageal temperature and sweat rates on the right and left forearms (Ogawa et al., 1989b).

side (Ogawa et al., 1989b) (Fig. 4).

There have been many other reports demonstrating that thermoregulatory

responses to heat load, such as heart rate (Germain et al., 1987; Cabanac and Caputa, 1979b), cutaneous vasodilation (Hirata et al., 1988), thermal behavior (Caputa and Cabanac, 1980), and thermal comfort (Brown and Williams, 1982) show a closer correlation with Tty than with Tes or other trunk temperatures. Furthermore, we have demonstrated that acclimation to heat by repeated controlled trunk hyperthermia was suppressed when combined with clamping of Tty at normal levels by face cooling, indicating that Tty offers a better estimate of central thermal input to the thermoregulatory mechanism (Ogawa et al., 1989a).

References

- Baker, M.A., Stocking, R.A. and Meehan, J.P. (1972) 'Thermal relationship between tympanic membrane and hypothalamus in conscious cat and monkey', *J. Appl. Physiol.*, 32, 739-742.
- Benzinger, T.H. (1959) 'On physical heat regulation and the sense of temperature in man', *Proc. Nat. Acad. Sci.*, 45, 645-659.
- Benzinger, T.H. and Taylor, G.W. (1963) 'Cranial measurements of internal temperature of man', in: *Temperature: its Measurement and control in Science and Industry*, Reinhold, New York, vol.3, p. 111-120.
- Brengelmann, G.L. (1987) 'Dilemma of body temperature measurement', in: *Man in Stressful Environments, Thermal and Work Physiology*, C.C. Thomas, Springfield, p.5-22.
- Brinnel, H. and Cabanac, M. (1989) 'Tympanic temperature is a core temperature in humans', *J. Therm. Biol.*, 14, 47-53.
- Brown, G.A. and Williams, G.M. (1982) 'The effect of head cooling on deep body temperature and thermal comfort in man', *Aviat. Space Environ. Med.*, 53:583-586.
- Cabanac, M. and Brinnel, H. (1985) 'Blood flow in the emissary veins of the human head during hyperthermia', *Eur. J. Appl. Physiol.*, 54, 172-176.
- Cabanac, M. and Caputa, M. (1979a) 'Natural selective cooling of the human brain: evidence of its occurrence and magnitude', *J.*

Physiol., 286, 255-264.

Cabanac, M. and Caputa, M. (1979b) 'Open loop increase in trunk temperature produced by face cooling in working humans', *J. Physiol.*, 289, 163-174.

Cabanac, M., Germain, M. and Brinnel, H. (1987) 'Tympanic temperature during hemiface cooling', *Eur. J. Appl. Physiol.*, 56, 534-539.

Caputa, M. and Cabanac, M. (1980) 'Muscular work as thermal behavior in humans', *J. Appl. Physiol.*, 48, 1020-1023.

Carlsten, W.I. and Grimby, G (1958) 'Rapid changes in human right heart blood temperature at variations in venous return', *Scand. J. Clin. Lab. Invest.*, 10, 397-401.

Cooper, K.E., Cranston, W.I. and Snell, E.S. (1964) 'Temperature in the external auditory meatus as an index of central temperature changes', *J. Appl. Physiol.*, 19, 1032-1035.

Cooper, K.E. and Kenyon, J.R. (1957) 'A comparison of temperatures measured in the rectum, oesophagus, and on the surface of the aorta during hypothermia in man', *Br. J. Surg.*, 44, 616-619.

Cranston, W.I., Gerbrabdy, J. and Snell, E.S. (1954) 'Oral, rectal and oesophageal temperatures and some factors affecting them in man', *J. Physiol.*, 126, 347-358.

Davis, F.M., Barnes, P.K. and Bailey, J.S. (1981) 'Aural thermometry during profound hypothermia', *Anesth. Intens. Care*, 9, 124-128.

Deklunder, G., Dauzat, M., Lecroart, J-L., et al. (1991) 'Influence of ventilation of the face on thermoregulation in man during hyper- and hypothermia', *Eur. J. Appl. Physiol.*, 62, 342-348.

Dickey, W.T., Ahlgren, E.W. and Stephen, C.R. (1970) 'Body temperature monitoring via the tympanic membrane', *Surgery*, 67, 981-984.

Eichna, L.W., Berger, A.R., Rader, B. and Becker, W.H. (1951) 'Comparison of intracardiac and intravascular temperatures with rectal temperatures in man', *J. Clin. Invest.*, 30, 353-359.

Germain, M., Jobin, M. and Cabanac, M.

(1987) 'The effect of face fanning during recovery from exercise hyperthermia', *Can. J. Physiol. Pharmacol.*, 65, 87-91.

Gibbons, L.W. (1967) 'Body temperature monitoring in the external auditory meatus', *Aerospace Med.*, 38, 671-675.

Gibson, T.M., Redman, P.J. and Belyavin, A.J. (1981) 'Prediction of oesophageal temperatures from core temperatures measured at other sites in man', *Clin. Phys. Physiol. Meas.*, 2, 247-256.

Greenleaf, J.E. and Castle, B.L. (1972) 'External auditory canal temperature as an estimate of core temperature', *J. Appl. Physiol.*, 32, 194-198.

Hirata, K., Nagasaka, T., Noda, Y. et al. (1988) 'Finger vasodilation correlates with tympanic than esophageal temperature', *Eur. J. Appl. Physiol.*, 57, 735-739.

Hirata, K., Nagasaka, T., Tanabe, M., et al. (1990) 'Measurements of tympanic temperature during heat load induced by exercise' (in Japanese), *Jpn. J. Phys. Fit. Sports Med.*, 39, 628.

Ilsley, A.H., Rutten, A.J. and Runciman, W.B. (1983) 'An evaluation of body temperature measurement', *Anesth. Intens. Care*, 11, 31-39.

Jakobsson, J., Nilsson, A. and Carlsson, L. (1992) 'Core temperature measured in the auricular canal: comparison between four different tympanic thermometers', *Acta Anaesthesiol. Scand.*, 36, 819-824.

Jessen, C. and Kuhnen, G. (1992) 'No evidence for brain stem cooling during face fanning in humans', *J. Appl. Physiol.*, 72, 664-669.

Mairiaux, P., Sagot, J.C. and Candas, V. (1983) 'Oral temperature as an index of core temperature during heat transients', *Eur. J. Appl. Physiol.*, 50, 331-341.

Marcus, (1973) 'Some effects of radiant heating of the head on body temperature measurement at the ear', *Aerospace Med.*, 44, 403-406.

Mariak, Z., Lewko, J., Jadeszko, M. and Dudek, H. (1994) 'Cerebral and related temperatures in normothermic subjects', in:

Temperature Regulation: Recent Physiological and Pharmacological Advances, Birkhäuser, Basel, p. 139-144.

Masuda, M. and Uchino, K. (1978) 'A device for measuring tympanic membrane temperature in man', *Jikeikai Med. J.*, 25, 95-99.

McCaffrey, T.V., Geis, G.S., Chuns, J.M. et al. (1975) 'Effects of isolated head heating and cooling on sweating in man', *Aviat. Space Environ. Med.*, 46, 1353-1357.

Mead, J. and Bonmario, L. (1949) 'Reliability of rectal temperatures as an index of internal body temperature', *J. Appl. Physiol.*, 2, 97-109.

Nadel, E.R. and Horvath, S.M. (1970) 'Comparison of tympanic membrane and deep body temperatures in man', *Life Sci.*, 9, 867-875.

Nagasaka, T., Hiramatsu, M., Tanabe, M., et al. (1990) 'Role of the veins of the face in brain cooling during body warming in human subjects', *Jpn. J. Biometeor.*, 27, 113-120.

Nishita, M. (1992) 'Cerebrovascular disease and tympanic temperature' (in Japanese), *J. Aichi Med. Univ. Assoc.*, 20, 721-729.

Ogawa, T. (1994) 'Measurement of tympanic temperature and its significance in physiology and pathophysiology', *Biomed. Thermol.*, 13(4), 163-172.

Ogawa, T. and Asayama, M. (1987) 'Thermal and nonthermal control of sweating during rest and exercise', in: *Man in Stressful Environments: Thermal and Work Physiology*, C.C. Thomas, Springfield, p. 225-236.

Ogawa, T., Ohnishi, N., Yamashita, Y., et al. (1989a) 'Effect of facial cooling during heat acclimation process on adaptive changes in sweating activity', *Jpn. J. Physiol.*, 38, 479-490.

Ogawa, T., Sugenoya, J., Ohnishi, N., et al. (1992) 'Relative changes in bilateral tympanic temperatures observed by long-term continuous recording', *Jpn. J. Physiol.*, 42 (Suppl.), S281.

Ogawa, T., Sugenoya, J., Ohnishi, N., et al. (1993a) 'Effects of body and head positions

on bilateral difference in tympanic temperatures', *Eur. J. Appl. Physiol.* 67, 354-359.

Ogawa T., Sugenoya J., Ohnishi N., et al. (1993b) 'Bilateral differences in tympanic temperatures induced by vascular compression in the head and neck', *Jpn. J. Physiol.*, 43 (Suppl. 2), S 308.

Ogawa, T., Sugenoya, J., Sugino, F. and Nishida, N. (1995) 'Blood flow vs brain temperature', in: *Body Temperature and Metabolism*, IPEC, Tokyo, p. 145-148.

Ogawa, T., Yamashita, Y., Sugenoya, J., et al. (1989b) 'Evaluation of bilateral difference in tympanic temperature' (in Japanese), *Jpn. J. Biometeor.*, 26, 161-167.

Sawka, M.N. and Wenger, C.B. (1996) 'Thermoregulatory responses to acute-heat stress and heat acclimation', in: *Handbook of Physiology, Sec. 4, Environmental Physiology*, Vol. 1, Oxford Univ. Press, New York, p. 157-185.

Sharkey, A., Elliot, P., Lipton, J.M. and Giesecke, A.H. Jr. (1987) 'The temperature of the air within the external auditory meatus compared with esophageal temperature during anaesthesia and surgery', 12, 11-13.

Shiraki, K., Konda, N. and Sagawa, S. (1986) 'Esophageal and tympanic temperature responses to changes in core blood temperature during hyperthermia', *J. Appl. Physiol.*, 61, 98-102.

Shiraki, K., Sagawa, S., Tajima, F., et al. (1988) 'Independence of brain and tympanic temperatures in an unanesthetized human', *J. Appl. Physiol.*, 65, 482-486.

Soutsu, M. (1991) 'Thermal relationship between tympanic membrane and intracranial temperature in human' (in Japanese), *Clin. Thermometry*, 11 (2), 116-121.

Sugenoya, J., Kihara, M., Ogawa, T., et al. (1988) 'Effects of thyrotropin releasing hormone on human sudomotor and cutaneous vasomotor activities', *Eur. J. Appl. Physiol.*, 57, 632-638.

Sugenoya, J. and Ogawa, T. (1985) 'Characteristics of central sudomotor mechanism estimated by frequency of sweat

expulsions, *Jpn. J. Physiol.*, 35, 783-794.

Sugino, F., Ogawa, T., Umemura, S. et al. (1997) 'Effect of acetazolamide on cerebral blood flow and tympanic temperature in healthy subjects and patients with subacute aubarachnoid haemorrhage', *Eur. J. Appl. Physiol.*, 75, 252-255.

Tabor, M.W., Blaho, D.M. and Schriver, W.R. (1981) 'Tympanic membrane perforation: complication of tympanic thermometry during general anesthesia', *Oral Surg.*, 51, 581-583.

Tanabe, K. and Takaori, S. (1964) 'Effects of cooling and warming of the common carotid arteries on the brain and tympanic membrane temperatures in the rabbit', *Jpn. J. Pharmacol.*, 14, 67-79.

Togawa, T. (1985) 'Body temperature measurement', *Clin. Phys. Physiol. Meas.*, 6, 83-108.

Umeyama T, Ogawa T, Kandori Y, et al. (1993) Bilateral difference in cerebral blood flow following stellate ganglion block, estimated by brain scintigraphy' (in Japanese), *Auton. Nerv. Syst.*, 30, 181-182.

Vale, R.J. (1981) 'Monitoring of temperature during anesthesia', *Int. Anesthesiol. Clin.*, 19, 61-83.

Wallace, C.T., Marks, W.E., Adkins, W.Y., et al. (1974) 'Perforation of the tympanic membrane, a complication of tympanic thermometry during anesthesia', *Anesthesiology*, 41, 290-291.

Webb, G.E. (1973) 'Comparison of esophageal and tympanic temperature monitoring during cardiopulmonary bypass', *Anesth. Analg.*, 52, 729-733.

Whitby, J.D. abd Dunkin (1968) 'Temperature difference in the oesophagus', *Br. J. Anaesth.*, 40, 991-995.