

Transcutaneous PCO₂ Measurement at Low Temperature for Reliable and Continuous Free Flap Monitoring: Experimental and Clinical Study

Yoshiro Abe, MD
Ichiro Hashimoto, MD, PhD
Keiichi Goishi, MD, PhD
Keisuke Kashiwagi, MD
Masahiro Yamano, MD
Hideki Nakanishi, MD, PhD

Background: Measurement of transcutaneous oxygen pressure (TcPO₂) and transcutaneous carbon dioxide pressure (TcPCO₂) has been used for free flap monitoring. Because these values are obtained with sensor probes heated to 44°C, there is potential for low-temperature burns on skin flaps. We measured TcPO₂ and TcPCO₂ at 37°C in both animals and humans to determine the feasibility and safety of the procedure as a postoperative flap monitoring method.

Methods: Twelve epigastric island flaps were elevated in rabbits, and TcPO₂ and TcPCO₂ were measured at 37°C before and after ligation of the pedicles. In addition, TcPO₂ and TcPCO₂ at 37°C were measured in healthy men. Subsequently, the method was applied to postoperative monitoring of free flaps in 49 clinical cases.

Results: TcPO₂ and TcPCO₂ values were significantly affected by the experimental flap elevation. A rapid increase in TcPCO₂ was observed with both arterial and venous occlusion. In the healthy men, TcPO₂ and TcPCO₂ were measurable at all skin surface sites. In the clinical cases of free flap transfer, TcPO₂ values remained very low for at least 72 hours. TcPCO₂ values ranged from 40 to 70 mm Hg for 72 hours in more than 80% of cases. In 2 cases, TcPCO₂ values increased to more than 90 mm Hg, and exploration surgery was performed. These compromised flaps were saved by reanastomosis of the veins.

Conclusions: Continuous monitoring of TcPCO₂ at 37°C can provide objective information and alert doctors and nurses to the need for checking the free flap. (*PRS GO 2013;1:e16; doi:10.1097/GOX.0b013e3182936cd0; Published online 13 May 2013.*)

The success rate for free tissue transfer is now more than 95%^{1,2} because of improved procedures and increased knowledge of vascular supply patterns of the flaps. Initial success rates are approaching 100%. Nevertheless, a transferred flap

can be lost, and microsurgeons expend considerable effort to salvage the failing flap or at least manage the flap conservatively.³ The importance of postoperative flap monitoring for early detection of circulatory disturbance is therefore understood. Although

From the Department of Plastic and Reconstructive Surgery, The University of Tokushima Graduate School, Tokushima, Japan. Drs. Abe and Hashimoto contributed equally to this work and should be considered co-first authors.

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many monitoring methods have been reported, the ideal monitoring method for detecting flap compromise has not been determined.⁴

Flap monitoring methods include transcutaneous oxygen pressure (TcPO₂) measurement^{5,6} and transcutaneous carbon dioxide pressure (TcPCO₂) measurement.⁷ The instrument for measuring TcPO₂ and TcPCO₂ was originally developed to measure partial pressure of arterial oxygen (PaO₂) and partial pressure of arterial carbon dioxide (PaCO₂) with a skin probe heated to 44°C. However, a low-temperature skin burn can result when TcPO₂ and TcPCO₂ are monitored continuously at 44°C.^{5,7}

The aim of this 3-part study was to investigate the feasibility of monitoring TcPO₂ and TcPCO₂ in skin flaps with a probe heated to 37°C. TcPO₂ and TcPCO₂ were first measured at 37°C in rabbit epigastric island flaps that were subjected to arterial or venous occlusion. TcPO₂ and TcPCO₂ were then measured at 37°C at 8 different surface skin sites in healthy human adults. Subsequently, a clinical study was conducted in which TcPO₂ and TcPCO₂ were measured at 37°C in 49 free flaps, two of which proved to be compromised.

MATERIALS AND METHODS

Measurements in the experimental and clinical studies were performed with a TCM4 monitor (Radiometer Medical ApS, Copenhagen, Denmark). TcPO₂ and TcPCO₂ are measured simultaneously with the device's sensor; the probe, which allows measurement of TcPO₂ and TcPCO₂ at the same site and the same time, contains a Clark-type electrode for measurement of TcPO₂ and a pH-sensitive glass electrode for measurement of TcPCO₂. The probe, which was fixed to the skin surface with adhesive tape, was thermostatically adjusted to 37°C. Room temperature was controlled between 18°C and 24°C during measurements in both the animal and clinical studies. Experimental procedures were approved by the institutional animal care and use committee of The University of Tokushima and were carried out in accordance with committee guidelines. The human subjects were fully informed of the reason for and the importance of TcPO₂ and TcPCO₂ measurement.

Part 1: Animal Experiment For Testing The Effects Of Flap Elevation And Pedicle Occlusion By Low-Temperature Measurement Of Tcpo₂ And Tcpc_{o2}

Twelve male Japanese white rabbits weighing 3.0–3.5 kg were used for the study. All were maintained under standard housing conditions and allowed water and standard dry rabbit feed ad libitum. The rabbits were anesthetized with intravenous pentobarbital (Somnopenyl) (64.8 mg/mL, Kyoritsu Seiyaku, To-

kyo, Japan), and an epigastric island flap (17 cm × 5 cm) was elevated in each rabbit on the basis of the superficial inferior epigastric artery and vein, according to a well-described technique.^{8–10} After the flap was sewn back into its original place, the probe was placed on the skin 4 cm away from the distal edge of the flap. The animals were divided into 2 groups for arterial or venous occlusion produced by ligation of the superficial inferior epigastric artery or vein. TcPO₂ and TcPCO₂ were measured immediately before and 20 minutes after flap elevation (before ligation of the vascular pedicle) and at 5, 10, 20, 30, 60, 90, and 120 minutes after ligation of the vascular pedicle.

Part 2: Study Of Low-Temperature Tcpo₂ And Tcpc_{o2} Measurement At Different Body Sites In Healthy Humans

We measured TcPO₂ and TcPCO₂ at 8 superficial sites in 10 healthy male volunteers (age range, 24–36 y; mean age, 30.4 y): the forehead, cheek, back, abdomen, volar aspect of the forearm, lateral aspect of the thigh, posterior aspect of the leg, and anterior aspect of the tibia. We did this to investigate whether measurement of these values with a probe adjusted thermostatically to 37°C was possible at various donor sites.

Part 3: Low-Temperature Monitoring Of Tcpo₂ And Tcpc_{o2} In Clinical Cases Of Free Flap Transfer

This part of the study comprised 49 patients [32 men and 17 women ranging in age from 19 to 84 y (mean, 54.8 y)] undergoing free flap transfer at Tokushima University Hospital between January 2002 and July 2011. All 49 patients were of normal nutritional status before surgery. The free flaps comprised 23 anterolateral thigh flaps, 10 latissimus dorsi musculocutaneous flaps, 5 fibular osteocutaneous flaps, 4 medial plantar flaps, 4 thoracodorsal artery perforator flaps, 1 radial forearm flap, 1 deep inferior epigastric perforator flap, and 1 transverse rectus abdominis musculocutaneous flap. TcPO₂ and TcPCO₂ were measured continuously for at least the first 72 hours after the transfer. That is, values were recorded immediately upon the patient's postsurgical transfer to the intensive care unit and then every hour on postoperative day 1, every 2 hours on postoperative day 2, every 4 hours on postoperative day 3, and thereafter.

STATISTICAL ANALYSIS

Measured values are shown as median (range). In the animal flap experiment, differences between values before and after flap elevation and differences between values before and after ligation of vascular pedicles were analyzed by Wilcoxon signed-rank

test for nonparametric data. In the clinical free flap study, values recorded at 24, 48, and 72 hours after the transfer were compared to values recorded immediately after the transfer, and differences were analyzed by Wilcoxon signed-rank test for nonparametric data.

RESULTS

Part 1: Animal Experiment for Testing the Effects of Flap Elevation and Pedicle Occlusion by Low-temperature Measurement of TcPO₂ and TcPCO₂

In the rabbit epigastric flaps subjected to arterial occlusion ($n = 6$), TcPO₂ before flap elevation [44.5 (30–68) mmHg] decreased significantly to 3.5 (2–8) mmHg after elevation ($P = 0.031$). After arterial ligation, TcPO₂ decreased significantly to 2 (1–3) mmHg at 5 minutes ($P = 0.031$), and it remained below 2.0 mmHg to the end of the study period. In this group, TcPCO₂ before flap elevation [57 (53–76) mmHg] increased significantly to 85.5 (67–105) mmHg after elevation ($P = 0.031$). After arterial ligation, TcPCO₂ increased significantly to 98 (71–120) mmHg at 5 minutes ($P = 0.031$), and it increased gradually to as much as 145.5 (128–168) mmHg by 90 minutes (Fig. 1A).

In the flaps subjected to venous occlusion ($n = 6$), TcPO₂ before flap elevation [65 (26–71) mmHg] decreased significantly to 13 (2–27) mmHg after elevation ($P = 0.031$). After venous ligation, TcPO₂ decreased significantly to 7 (2–10) mmHg at 5 minutes ($P = 0.031$), and it remained below 7.0 mmHg to the end of the study period. In this group, the TcPCO₂ value before flap elevation [56 (55–66) mmHg] increased significantly to 75.5 (67–86) mmHg after elevation ($P = 0.031$). After venous ligation, TcPCO₂ increased significantly to 85 (76–96) mmHg at 5 minutes ($P = 0.031$), and it continued to increase to as much as 126 (119–158) mmHg by 90 minutes (Fig. 1B).

Part 2: Study of Low-temperature TcPO₂ and TcPCO₂ Measurement at Different Body Sites in Healthy Adults

Among the 10 healthy subjects in whom different monitoring sites were investigated, TcPO₂ was lower on the face than at other sites. TcPCO₂ was higher on the face (up to 70 mmHg) than elsewhere (values elsewhere never exceeded 60 mmHg) (Fig. 2).

Part 3: Low-temperature Monitoring of TcPO₂ and TcPCO₂ in Clinical Cases of Free Flap Transfer

None of the 49 patients who underwent free flap transfer died or suffered a critical setback owing to the original defect during the intraoperative period. There were no complications associated with use of

the probe, and presence of the probe elicited no complaints from the patients.

Median TcPO₂ was 4 (1–47) mmHg immediately after flap transfer (Fig. 3A). TcPO₂ values immediately after transfer and at 24, 48, and 72 hours after transfer were below 10 mmHg in 71.4%, 87.8%, 86.7%, and 93.9% of patients, respectively. Median TcPCO₂ was 56 (40–85) mmHg immediately after flap transfer (Fig. 3B). TcPCO₂ values immediately after transfer and at 24, 48, and 72 hours after transfer ranged between 40 and 70 mmHg in 81.7%, 85.4%, 93.3%, and 84.8% of patients, respectively. TcPO₂ and TcPCO₂ values at 24, 48, and 72 hours after transfer decreased compared with the values immediately after transfer.

The lowest and highest TcPO₂ and TcPCO₂ values obtained during the first 72 hours after transfer in each case are shown in Figures 4A and B, respectively. The lowest TcPO₂ values ranged from 0 to 20 mmHg and were less than 10 mmHg in 96% (47/49) of flaps. The lowest TcPCO₂ values ranged from 23 to 64 mmHg. The highest TcPO₂ values ranged from 2 to 47 mmHg, and the highest TcPCO₂ values ranged from 45 to 112 mmHg. Two cases in which the TcPCO₂ values increased to 92 and 112 mmHg required exploration.

A sudden increase in TcPCO₂ was noted postoperatively in 2 patients, one at 6 hours and the other at 60 hours after flap transfer (Table 1 and Figs. 5–7). Immediate exploration was performed, and venous thrombi were removed in both cases. TcPCO₂ decreased immediately after venous reanastomosis. The transferred flaps were rescued and fully survived. All flaps that survived the initial operation showed TcPCO₂ values below 88 mmHg. We experienced only 2 cases of flap compromise; however, both positive predictive value and negative predictive value were 100% when TcPCO₂ exceeding 90 mmHg was used to determine that revision surgery was necessary (Fig. 4B). We could not confirm significant changes in TcPO₂ values after the reanastomoses because the values remained below 10 mmHg. Accordingly, the decrease in TcPO₂ values could not be used to detect the circulatory disturbance.

DISCUSSION

Free tissue transfer depends on the patency of pedicle vessels for survival. The sooner the circulatory disturbance in the flap is detected, the sooner the exploration and rescue can be performed. Thus, numerous techniques have been investigated and used in search of the ideal free flap monitoring method. Two basic types of measurement methods exist. First, blood flow through the vascular pedicle

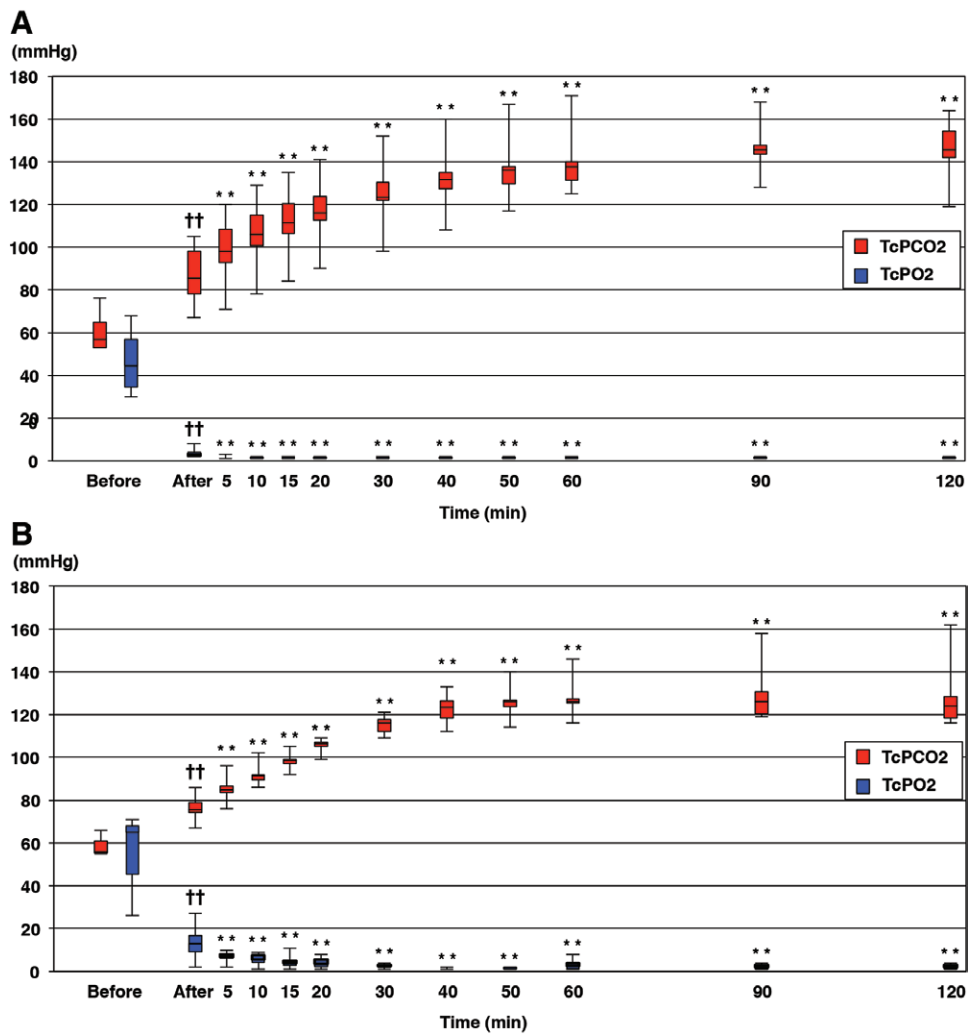


Fig. 1. TcPO₂ and TcPCO₂ values in rabbit epigastric flaps. Values are expressed as median and range. “Before” refers to before flap elevation, “after” refers to 20 min after flap elevation (before ligation of vascular pedicle), and “time” refers to elapsed time after ligation of vascular pedicle. A, Graph showing TcPO₂ and TcPCO₂ values before and after rabbit epigastric flap elevation and arterial occlusion. B, Graph showing TcPO₂ and TcPCO₂ values before and after rabbit epigastric flap elevation and venous occlusion. ††*P* < 0.01 vs values before flap elevation, by Wilcoxon signed-rank test. ***P* < 0.01 vs values before ligation of the artery or vein, by Wilcoxon signed-rank test.

can be monitored by means of an implantable Doppler probe or by color duplex sonography.¹¹ Second, blood flow in the peripheral circulation can be assessed by observation of flap skin color,¹² by capillary refilling, by monitoring with a handheld Doppler probe, by near-infrared spectroscopy,¹³ by use of a laser Doppler flowmeter,^{14,15} or by measuring the temperature of flaps,¹⁶ tissue oxygen tension,^{17,18} and TcPO₂ and TcPCO₂ with a probe heated to 44°C.⁵⁻⁷

The TcPO₂ and TcPCO₂ probe detects oxygen and carbon dioxide coming from capillaries in the dermis through the epidermis and corneum. The oxygen is consumed by the epidermal cells and by the TcPO₂ probe on the corneum.¹⁹ The carbon dioxide

is produced by the epidermal cells and is not consumed by the probe. This explains why the TcPO₂ is lower than the PaO₂ and the TcPCO₂ is higher than the PaCO₂ when TcPO₂ and TcPCO₂ are measured by unheated probes. When a heated probe is used, the skin temperature reaches approximately 44°C, making the TcPO₂ value closer to the PaO₂ value. The TcPCO₂ value measured at 44°C becomes higher than that measured at 37°C. Although a heated electrode is not required to measure TcPCO₂, the measurement is usually carried out under heated conditions for faster reactivity of TcPCO₂ upon the change in PaCO₂.²⁰ A low-temperature burn may result from heating the skin to 44°C for more than 3

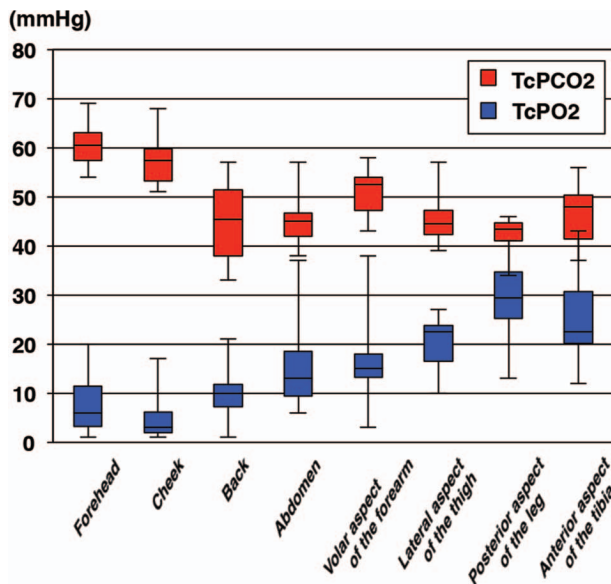


Fig. 2. Boxplot showing TcPO₂ and TcPCO₂ values (median, upper and lower quartiles, and range) at 8 different sites in healthy adults. Values were obtained with probes thermally controlled at 37°C.

hours during continuous monitoring.^{5,7} Therefore, the monitoring site must be altered every 3–4 hours to avoid thermal injury, and the electrode must be recalibrated before placement. Frequent reattachment often causes inaccurate monitoring due to air bubbles trapped in the electrode, improper placement, or a damaged sensor membrane.

Our experimental study revealed that flap elevation and ligation of the vascular pedicle affected the TcPO₂ and TcPCO₂ values. This suggests that the measurement of both values can perhaps detect any circulatory disturbance caused by arterial or venous ischemia. However, the TcPO₂ values remain very low after flap elevation. Trends in the changing TcPO₂ and TcPCO₂ values were quite similar between arterial occlusion and venous occlusion. Thus, it is difficult to differentiate between the 2 types of occlusion through TcPO₂ and TcPCO₂ measurements.

In our study of different monitoring sites, TcPO₂ and TcPCO₂ values obtained at all measurement sites at 37°C were lower than previously reported TcPO₂ and TcPCO₂ values obtained at 44°C or 45°C.^{19,21} With measurement at 37°C, TcPO₂ and TcPCO₂ values on the face differed from those on other body surfaces. These differences are also found with measurement at 44°C.¹⁹ Thus, the TcPO₂ and TcPCO₂ values of skin flaps obtained from various donor sites can be measured at 37°C.

TcPO₂ values on clinical free flaps are characteristically low in comparison to TcPCO₂ values. TcPO₂ values on the skin are reported to vary not only in

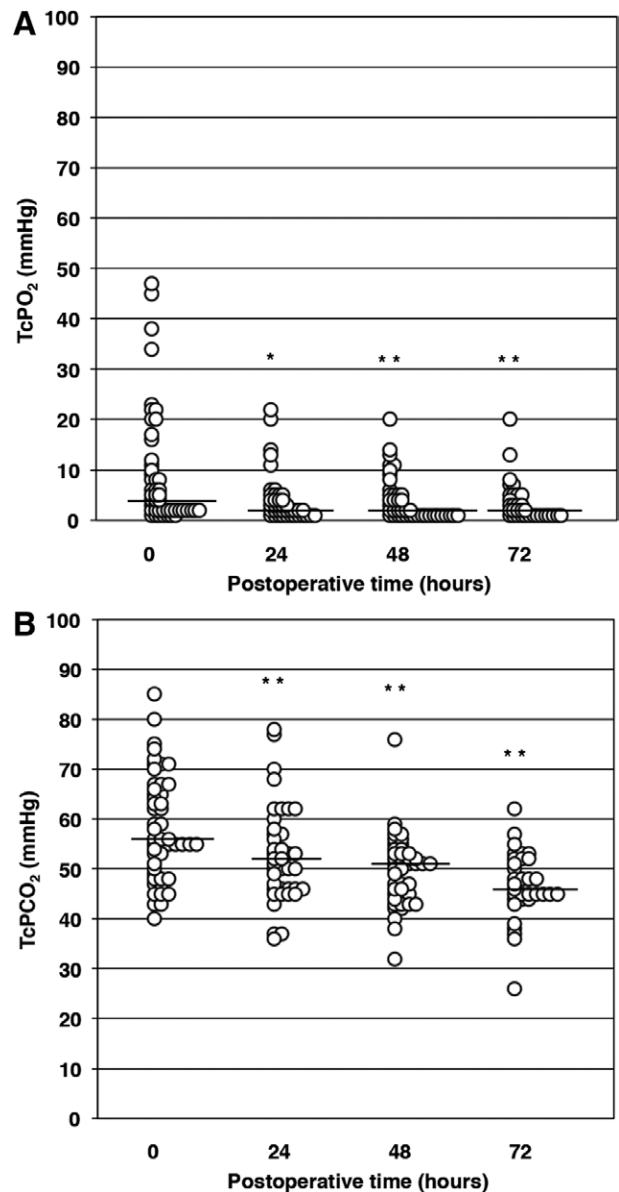


Fig. 3. Clinical postoperative TcPO₂ and TcPCO₂ values obtained with probes thermally controlled at 37°C. Circles represent individual patients. A, Graph of TcPO₂ values obtained immediately after surgery (0h) and at 24-h intervals thereafter. Bars indicate the median values at each time point. B, Graph of TcPCO₂ values obtained immediately after surgery (0h) and at 24-h intervals thereafter. Bars indicate the median values at each time point. **P* < 0.05 vs values at 0h (ie, immediately after surgery), by Wilcoxon signed-rank test. ***P* < 0.01 vs values at 0h (ie, immediately after surgery), by Wilcoxon signed-rank test.

relation to the actual perfusion situation, density of the capillary network, and temperature but also in relation to regional factors, that is, thickness of the stratum corneum and density of the subdermal sebaceous glands.^{19,22–24} Flap elevation decreased TcPO₂ values in our animal study. The low TcPO₂ values

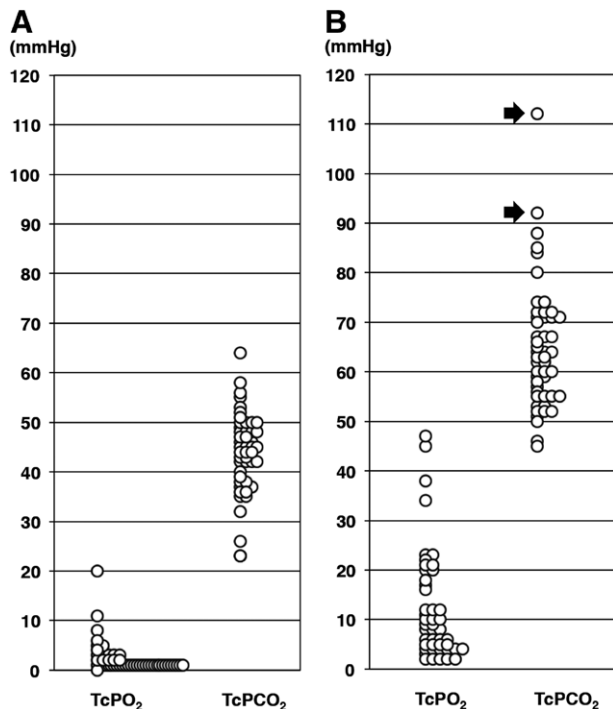


Fig. 4. Highest and lowest clinical TcPO₂ and TcPCO₂ values measured at 37°C. Circles represent individual patients. A, Graph showing the lowest TcPO₂ and TcPCO₂ values in the 49 free flaps. B, Graph showing the highest TcPO₂ and TcPCO₂ values in the 49 free flaps. Two patients with a TcPCO₂ value more than 90 mm Hg (arrows) underwent exploration.

may reflect postoperative edema of the flap skin or the vasospasm that occurs during elevation of the flap.^{7,8,25}

TcPCO₂ values are measurable at 37°C even after clinical free flap elevation. TcPCO₂ is not readily influenced by the cutaneous factors described above.^{20,23} We suppose that TcPCO₂ is influenced by the severe circulatory disturbance such as venous or arterial ischemia rather than the cutaneous factors.⁷ Reasons for the decrease in TcPO₂ and TcPCO₂ we observed every 24 hours after the transfer are not clear. The decrease in TcPCO₂ may reflect a settling down of the circulatory condition, whereas the decrease in TcPO₂ may mean continuing edema of the flap skin.

When critical circulatory failure occurs in the free flap, we can expect to detect the failure by the decrease in TcPO₂ and increase in TcPCO₂. The low-

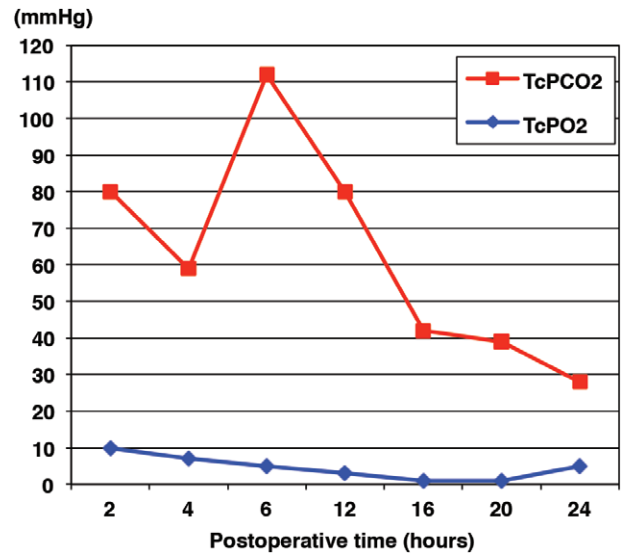


Fig. 5. Graph showing TcPO₂ and TcPCO₂ values after transfer in a case requiring exploration. Serious circulatory disturbance was suspected because of the sudden increase in TcPCO₂ to more than 90 mm Hg 6 h after flap transfer. Exploration was performed immediately, and a venous thrombus was removed. TcPCO₂ decreased promptly, and the flap survived completely. TcPO₂ did not change significantly before or after exploration.

est TcPO₂ values measured in the 2 patients undergoing removal of a thrombus in the vascular pedicle and those measured in patients who did not require exploration were very low and not distinguishable. The highest TcPCO₂ values measured in the 47 patients who did not require exploration were less than 90 mm Hg. The highest values measured in the 2 patients who underwent reoperation were more than 90 mm Hg, and these values decreased to less than 80 mm Hg after removal of the thrombi. This means a line can be drawn at 90 mm Hg of TcPCO₂ to indicate exploratory surgery. This value (90 mm Hg) is the same as that reported in a previous study performed at 44°C.⁷ TcPCO₂ of more than 90 mm Hg is the critical limit for circulatory failure of a free flap.

The TcPCO₂ monitoring method does not involve direct observation of blood flow to determine the viability of skin flaps. A TcPCO₂ of 90 mmHg might not be definitive for a diagnosis of flap failure; TcPCO₂ values in some of our flaps that survived were very close to this cutoff value in the present study. Clini-

Table 1. Details of the 2 Cases Requiring Exploration

Patient	Place of Defect (Cause)	Flap Type	Highest TcPCO ₂ (mm Hg)
51-year-old man	Foot (injury)	Fibular o-c flap combined with soleus muscle	112
71-year-old woman	Cheek (SCC)	ALT flap combined with VLM	92

ALT, anterolateral thigh; o-c, osteocutaneous; SCC, squamous cell carcinoma; VLM, vastus lateralis muscle.

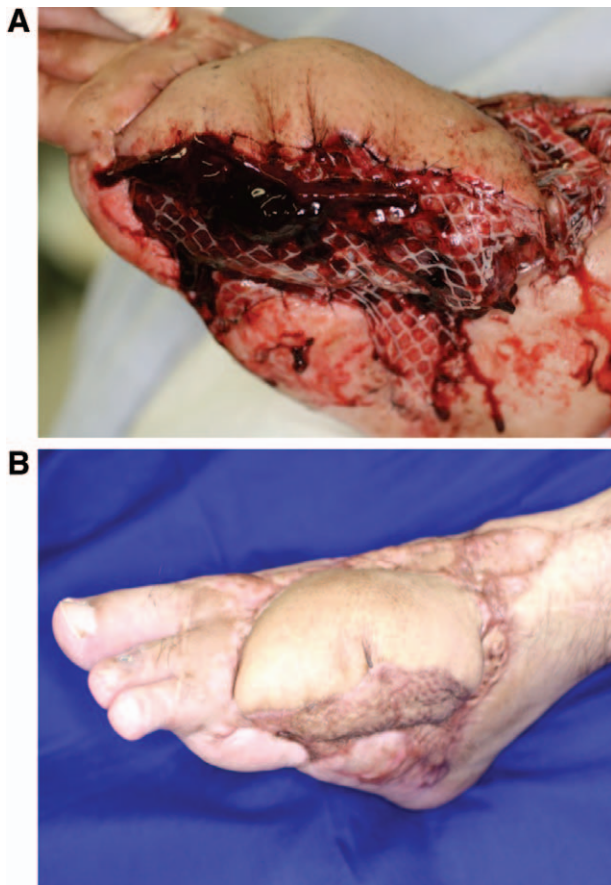


Fig. 6. Photographs obtained in the case charted in Figure 5. A, Photograph taken before exploration. The color of the skin flap before exploration is normal and not indicative of the underlying congestion. B, Photograph taken 6 mo later.

cal assessment that includes the pinprick test and observation of flap color remains the gold standard for evaluation of circulatory failure. We believe that final judgment for exploration must include clinical assessment. However, changes in the skin color of the flap can seem vague and assessment is subjective, especially for an untrained doctor or nurse, and such assessment does not equal continuous nor quantitative monitoring. Monitoring of TcPCO₂ at 37°C can be performed continuously without burning the skin. When an alarm is set for a TcPCO₂ value of 90 mm Hg, even an untrained doctor or nurse can be alerted to check for circulatory failure because the critical TcPCO₂ value is clear, objective, and easily understood.

CONCLUSIONS

In our study, TcPO₂ and TcPCO₂ values measured at 37°C were affected by flap elevation and arterial and venous ischemia. However, the TcPO₂ value was not particularly useful for detecting circulatory failure of free flaps because this value remained very low after free flap transfer. On the basis of our study find-

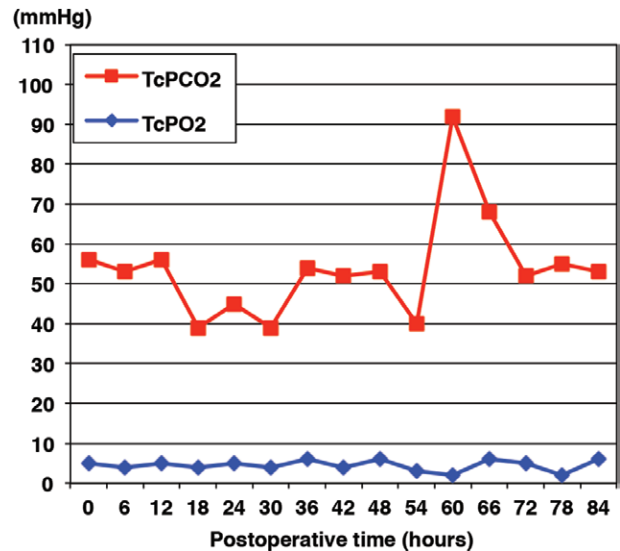


Fig. 7. Graph showing TcPO₂ and TcPCO₂ values after flap transfer in the second case requiring exploration. TcPCO₂ increased suddenly to 92 mm Hg at 60 h after transfer. Exploration was performed, and a venous thrombus was removed. The TcPCO₂ decreased promptly, and the flap survived completely. TcPO₂ did not change significantly before or after exploration.

ings, we suggest a TcPCO₂ value of 90 mm Hg to be the point at which free flap failure is indicated. The measurement procedure is noninvasive, safe, continuous, quantitative, easy to understand, and commercially available. We believe that this method is useful as an initial alert to the possibility of flap compromise and the need for further checking and that it can reduce the risk of flap failure by early detection of circulatory disturbance in the transferred flap.

Ichiro Hashimoto, MD, PhD,

Department of Plastic and Reconstructive Surgery,
The University of Tokushima Graduate School,

Kuramoto-cho,

Tokushima 770-8503, Japan.

E-mail: ihplast@clin.med.tokushima-u.ac.jp.

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