

Transcutaneous CO₂ Pressure Monitoring Increases Salvage Rates after Free Tissue Transplantation for Extremity Reconstruction

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Background: Although free tissue transplantation (FTT) is an essential technique in extremity functional reconstruction, postoperative blood flow disturbance is one of the critical complications leading to transplanted tissue necrosis. Early detection of this complication may prevent tissue failure by prompt improvement of blood flow. The aim of this study was to determine whether transcutaneous carbon dioxide pressure (TcPCO₂) monitoring increases the salvage rates after FTT.

Methods: We retrospectively reviewed 75 consecutive patients who underwent FTT for extremity reconstruction with TcPCO₂ monitoring postoperatively between December 2016 and September 2021.

Results: Extremity reconstruction was performed in 53 cases due to trauma, 20 cases due to infection, and two cases due to tumor resection for tissue defects. The overall success rate of the FTT was 98.7%, with 13 complications. Of the 11 patients who underwent reoperation, nine had thrombosis and two had vascular strangulation. However, when reoperation was decided, none of the reoperation cases still exhibited any deterioration in the Doppler or clinical assessment. All reoperated cases were salvaged. Of the two patients who did not undergo reoperation, one had failed flaps and one had partial skin necrosis. With a TcPCO₂ cutoff value of 70 mm Hg, the sensitivity and specificity for detecting complications due to impaired blood flow were 100% and 93.5%, respectively.

Conclusions: TcPCO₂ monitoring was performed after FTT for extremity reconstruction, and all cases of reoperation were salvaged. TcPCO₂ monitoring can detect impaired postoperative blood flow critically earlier than clinical assessments and may increase salvage rates of transplanted tissue. (*Plast Reconstr Surg Glob Open* 2022;10:e4467; doi: 10.1097/GOX.0000000000004467; Published online 19 August 2022.)

INTRODUCTION

Free tissue transplantation (FTT) is an essential technique in the functional reconstruction of extremities and is a standard method of tissue defect reconstruction. However, there are serious complications with FTT, and postoperative blood flow failure can lead to tissue necrosis. FTT has been proven reliable, with reported success

rates generally in excess of 90%.¹⁻³ However, FTT to the extremities, particularly the lower limbs, has been shown to have a high incidence of vascular complications and necrosis.^{4,5} To improve the success rate of FTT, early recognition of postoperative impaired blood flow is mandatory; tissue necrosis can be avoided by urgent blood flow restoration. The gold standard for postoperative flap monitoring is the clinical evaluation of the flap's color, capillary refill, turgor, and temperature. However, clinical monitoring requires substantial expertise and experience, and the flap salvage rates are not very high, reportedly 30%–70% when monitored by clinical evaluation alone.⁶⁻⁸

Recently, various monitoring devices have been used after FTT, including surface temperature probes, implantable Doppler systems, color duplex sonography, laser Doppler flowmetry, visible light spectroscopy, and near-infrared spectroscopy.⁹⁻¹¹ The ideal monitoring equipment should be noninvasive, easy-to-use, provide real-time flap perfusion data, and have a high level of sensitivity and specificity for detecting impaired blood flow.¹¹

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One monitoring method after FTT is to measure the transcutaneous carbon dioxide pressure (TcPCO₂). Elevated levels of TcPCO₂ measured from the skin flaps indicate increased carbon dioxide production due to increased cellular respiration or impaired gas exchange into the capillaries, indicating stagnation of the skin's microcirculation.¹² The reliability of TcPCO₂ monitoring after FTT has been reported, but there is little reference to flap salvage.^{13,14} In this study, we hypothesized that continuous monitoring of TcPCO₂ values would allow early detection of impaired blood flow to transplanted tissues and increase the salvage rate of FTT for extremity tissue defects.

PATIENTS AND METHODS

We retrospectively reviewed 75 consecutive patients who underwent FTT for extremity functional reconstruction and used a TcPCO₂ monitor as a postoperative monitoring tool between December 2016 and September 2021. A TcPCO₂ monitor was worn postoperatively for 7 days in addition to assessment of the flap's color and using Doppler ultrasonography. Specifically, the charge nurse checked them every hour and sent the information of the flap status to the doctor in charge. In all cases, prostaglandin was administered intravenously for 7 days postoperatively. When the TcPCO₂ value was greater than or equal to 70 mm Hg during the regular postoperative check, the charge doctor was called immediately. When impaired blood flow was suspected by color duplex sonography, or the TcPCO₂ value continued to increase, reoperation was performed to check for anastomotic vessels. All 75 cases were investigated for demographics, the causes of tissue loss, the source of the free tissue, complications, reoperation, salvage rates, and success rates. We also calculated the sensitivity and specificity of the TcPCO₂ with a 70 mm Hg cutoff value for detecting impaired blood flow.

TcPCO₂ Monitor

The TCM5 FLEX (Radiometer K.K.) was used to measure the TcPCO₂ (Fig. 1). This device records the carbon dioxide and oxygen partial pressures on the skin's surface percutaneously and continuously in real time through a probe attached to the skin. Previous studies reported that the normal skin of healthy subjects did not exceed TcPCO₂ values of 70 mm Hg at any site.¹⁴ Therefore, we applied a cutoff value for the TcPCO₂ of 70 mm Hg.

RESULTS

The mean age of the 75 FTT patients (61 men and 14 women) with TcPCO₂ postoperative monitoring was 46.7 years. Upper and lower limb reconstructions were performed in 16 and 59 patients, respectively. The causes of tissue loss included trauma in 53 cases, infections such as osteomyelitis and infectious pseudarthrosis in 20 cases, and tumor resection in two cases. The transplanted tissues were harvested from the anterolateral thigh, latissimus dorsi, fibula, superficial circumflex iliac perforator, lateral upper arm, and dorsal pedis (Table 1). The overall success rate was 98.7%. Of the 75 FTTs with the TcPCO₂ monitor, 74 survived.

Takeaways

Question: Does transcutaneous CO₂ monitoring increase the salvage rate after free tissue transplantation for extremity reconstruction?

Findings: We retrospectively reviewed 75 consecutive patients who underwent free tissue transplantation for extremity reconstruction with transcutaneous CO₂ monitoring postoperatively. The overall success rate of the free tissue transplantation was 98.7%, with 13 complications. Of the 11 patients who underwent reoperation, nine had thrombosis and two had vascular strangulation. All reoperated cases had vascular problems, but all cases were salvaged.

Meaning: Transcutaneous CO₂ monitoring after free tissue transplantation can detect impaired postoperative blood flow early and may increase salvage rates.

Thirteen complications occurred (17.3%) (Table 2). In the 11 cases that were reoperated on, postoperative TcPCO₂ values exceeded 70 mm Hg and rose rapidly. When reoperation was decided, none of the cases still exhibited any deterioration in the flap's color or the Doppler assessment. Of the 11 patients who underwent reoperation, nine had thrombosis (arterial and venous thrombosis in three, arterial thrombosis in one, and venous thrombosis in five), and the remaining two had no thrombosis but had strangulated vessels. All reoperated cases were salvaged by reanastomosis or the release of strangulation (Fig. 2). In the two cases that were not reoperated on, the TcPCO₂ value was already above 70 mm Hg immediately after surgery, and the patients were just followed up without surgical consideration, even though there was little tendency for the pressure to decrease. Eventually, one patient developed a failed flap, and the other had partial necrosis of the flap.

All 13 patients with complications had TcPCO₂ greater than or equal to 70 mm Hg, with no false negatives, and the sensitivity for detecting complications due to blood flow disturbances was 100%. In other words, no blood flow disturbances occurred at TcPCO₂ below 70 mm Hg. The negative predictive value of a TcPCO₂ less than 70 mm Hg, which was considered to be free from vascular problems, was 100%. The specificity of a TcPCO₂ value of 70 mm Hg was 93.5%, with four false positives (ie, no complications occurred in four patients with pressure values greater than or equal to 70 mm Hg). In three cases, the TcPCO₂ value exceeded 70 mm Hg immediately after surgery, but later dropped and was only monitored continuously. In one remaining case, the TcPCO₂ value reached greater than or equal to 70 mm Hg 48 hours postoperatively, but the presence of blood flow in the anastomotic vessel was confirmed by color duplex sonography, and the patient was followed up by volume loading with a plasma substitute, wherein the TcPCO₂ rapidly decreased. Thus, the positive predictive value for vascular event with TcPCO₂ values greater than or equal to 70 mm Hg was reduced to 76.5%.

No complications were associated with the monitoring device.



Fig. 1. The TCM5 FLEX (Radiometer K.K.) for measuring the TcPCO₂ (A) and the probe (B).

DISCUSSION

Although FTT is a useful procedure for extremity tissue defects, the failure rate especially in the lower extremities is higher than anywhere else in the body. In a previous study involving multiple cases, the failure rate to the lower extremities was 15%–20%.^{4,5} One of the most important factors in the functional reconstruction of the lower

extremities by FTT is the selection of the appropriate recipient vessels.⁵ However, in posttraumatic reconstruction, it is often difficult to select an appropriate recipient vessel because the perivascular area around the injury site can develop posttraumatic vessel disease, becoming edematous, brittle, and gradually fibrotic; a similar course may occur for infection sites. Thus, these conditions may make

Table 1. Sources of Free Tissue Used

Type of Tissue	No.
Anterolateral thigh	45
Latissimus dorsi	
Latissimus dorsi only	16
Latissimus dorsi + rib	2
Latissimus dorsi + SCIP	1
Latissimus dorsi + serratus anterior muscle	1
Fibula	7
SCIP	1
Lateral upper arm	1
Dorsal pedis	1

SCIP, superficial circumflex iliac perforator flap.

it difficult to reconstruct lower extremity defects with FTT for trauma and infection.

However, in our case series, 78.7% of the cases were lower extremity cases, and 97.3% of the cases were due to trauma or infection, yet the success rate was 98.7%, which is similar to other sites. Thirteen patients (17.3%) developed complications related to impaired blood flow, but all 11 patients who underwent reoperation were rescued. The reoperation salvage rate was 100%, which was higher than the previously reported salvage rate with monitoring by clinical evaluation alone. This high salvage rate may be due to the use of TcPCO₂ monitoring, which alerts us earlier than clinical assessments after FTT. The two cases that did not undergo reoperation despite elevated postoperative TcPCO₂ over 70 mm Hg were in the early stage of the clinical study. We missed the timing of the reoperation because we still did not fully trust the monitor and prioritized the clinical evaluation at that time. Now TcPCO₂ monitoring is a top priority, and we decide on reoperation even if there is no change in clinical evaluation.

The TCM5 FLEX can measure the carbon dioxide and oxygen percutaneously, as a substitute for arterial carbon dioxide and oxygen partial pressures.¹⁵ Abe et al¹⁴ investigated changes in TcPCO₂ and oxygen pressure in a pedicled flap blood flow disturbance model using Japanese white rabbits. Although significant changes in the transcutaneous oxygen pressure were difficult to determine, the TcPCO₂ showed a significant increase. Therefore, they concluded that an elevated TcPCO₂ may indicate skin vascular insufficiency, and TcPCO₂ monitoring is useful after FTT.

In addition, Abe et al¹⁴ set the cutoff value to 90 mm Hg, based on the experimental results that TcPCO₂ values do not exceed 70 mm Hg in any part of normal healthy skin but are higher immediately after operation until the values stabilize, and reported 100% sensitivity and specificity, respectively. However, in the study of 49 free flaps, only two had complications related to impaired blood flow, so further investigation may be necessary. In contrast, we set the cutoff value to 70 mm Hg for greater sensitivity and found that the sensitivity and specificity for detecting impaired blood flow were 100% and 93.5%, respectively. This sensitivity and specificity are not low compared with other devices.^{9,16} Besides the application of monitoring devices, in a study of postoperative monitoring by measuring capillary glucose and lactate in the flap, the sensitivity and specificity were 98.5% and 99.5%, respectively.¹⁷

Table 2. Case Complications

Patient	Age (y)	Sex	Causes of Tissue Loss	Free Tissue	Complication	Reoperation	Time from Initial Surgery to Reoperation (h)
1	67	Women	Tibial osteomyelitis	FVFG	Arterial thrombosis	Reanastomosis by vein graft	6
2	71	Men	Infected tibial pseudarthrosis	FVFG	Venous thrombosis	Reanastomosis by vein graft	29
3	51	Men	Open fracture of tibia	ALT	Venous strangulation	Release of strangulation, additional venous anastomosis	18
4	52	Women	Infected tibial pseudarthrosis	FVFG	Venous thrombosis	Reanastomosis by vein graft	38
5	45	Women	Open fracture of tibia	ALT	Arterial and venous thrombosis	Reanastomosis by end-to-end	12
6	50	Men	Open fracture of tibia	LD	Flap failure	Reanastomosis by vein graft	36
7	16	Men	Tibial osteomyelitis	ALT	Venous thrombosis	Reanastomosis by vein graft	36
8	23	Men	Hand degloving injury	ALT	Partial flap necrosis	Reanastomosis by vein graft	51
9	43	Women	Forearm tumor	FVFG	Venous thrombosis	Reanastomosis by vein graft	36
10	64	Men	Open fracture of tibia	LD	Arterial and venous thrombosis	Reanastomosis by vein graft	51
11	66	Men	Open fracture of tibia	LD	Venous thrombosis	Reanastomosis by end-to-end	36
12	67	Men	Open fracture of tibia	LD	Arterial thrombosis	Reanastomosis by vein graft	14
13	41	Men	Open fracture of femur and tibia, popliteal artery injury	LD	Arterial strangulation	Release of strangulation	15
					Arterial and venous thrombosis	Reanastomosis by vein graft	43

ALT, anterolateral thigh; FVFG, free vascularized fibular grafting; LD, latissimus dorsi.

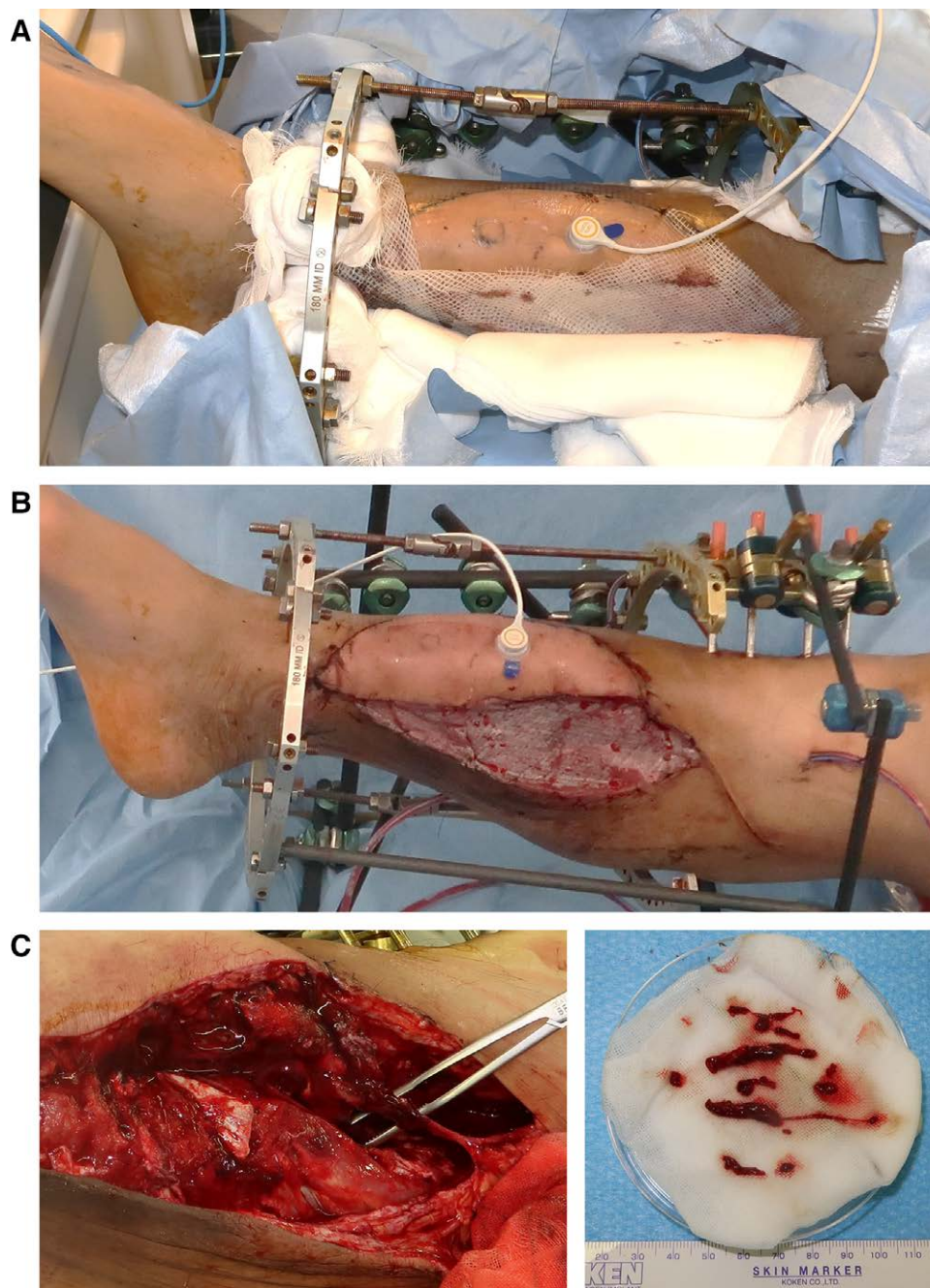


Fig. 2. A, A soft tissue and bone defect due to a right infected tibial pseudarthrosis was reconstructed with free vascularized fibular grafting. The TcPCO₂ rose to 70 mm Hg 29 hours after the TCM5 probe was attached to the skin paddle. At this time, there was no change in flap color tone or Doppler. B, In the reoperation room, TcPCO₂ rose to 120 mm Hg, and the flap color changed to the color of congestion. In this case, the change of the flap color occurred 3 hours after the TcPCO₂ exceeded the cutoff value. C, Thrombus was observed in the anastomosed vein. After thrombectomy, vascular reanastomosis was performed using a vein graft, and the graft tissue was salvaged.

However, our method is not invasive and is able to monitor continuously. Considering the possibility of detecting early blood flow failure, we think that a TcPCO₂ of 70 mm Hg is an appropriate cutoff value, despite the low specificity. Patients who underwent reoperation with this cutoff

value had a TcPCO₂ level greater than or equal to 70 mm Hg before changes in clinical monitoring following FTT. All patients who underwent reoperation had impaired blood flow, and TcPCO₂ monitoring with a cutoff value of 70 mm Hg allowed early detection of impaired blood flow.

With this monitoring method, the probe is easily and noninvasively attached to the flap; the TcPCO₂ values can then be observed in real time. Therefore, anyone can objectively assess blood flow failure after FTT using the appropriate cutoff value. However, because the carbon dioxide pressure is measured percutaneously, it is not indicated for cases without skin paddles, such as buried tissue transplantation. In addition, due to the possibility of dislodging the probe from the skin paddle and the need for periodic calibration, it is recommended that postoperative monitoring after FTT should not be performed with this device alone, but should be used in conjunction with conventional monitoring such as clinical evaluation.

The first limitation of this study was its retrospective design. Second, the number of salvage cases is still small, and the sensitivity and specificity may have a little discrepancy. Third, this study did not have a control group and relied on previous reports for comparison of salvage rates. However, this study demonstrated that TcPCO₂ monitoring is useful after FTT in extremity reconstruction, resulting in increased salvage rates after impaired blood flow. In the future, we need to carefully observe patients with TcPCO₂ values greater than or equal to 70 mm Hg in the immediate postoperative period. Further researching on the unacceptable rate of change in TcPCO₂ values immediately after operation may help to more accurately determine the protocol for TcPCO₂ monitoring after FTT.

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