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Original Article

Novel wireless laser doppler flowmeter-based investigation of earlobe vascular dynamics in cardiopulmonary exercise testing

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Abstract. [Purpose] A new wireless laser Doppler blood flowmeter has facilitated easier, more stable measurement of skin perfusion during exercise. However, earlobe blood flow during the cardiopulmonary exercise test remains unascertained. This study aimed to clarify the characteristics of earlobe blood flow during incremental exercise load in healthy individuals. [Participants and Methods] Among 25 healthy males (age 23.6 ± 2.5 years), cycle ergometer-based symptom-limited cardiopulmonary exercise test, after 4 minutes of rest, was conducted with a 4-minute 20W warm-up and a continuous 2W-increase in the work rate every 6 seconds; earlobe blood flow was measured using a wireless laser Doppler blood flowmeter. [Results] Compared with that at rest, earlobe blood flow increased significantly from 50% of exercise peak intensity to a maximum of 1.7 times, but decreased immediately after exercise. The earlobe blood flow %change did not significantly correlate with hemodynamic parameters and its inflection point 36.4% Load_{peak} was significantly lower than the anaerobic metabolic threshold 58.1% Load_{peak}. [Conclusion] In healthy participants, earlobe blood flow during cardiopulmonary exercise test increased gradually with low-intensity exercise from approximately 1.5 times the resting rate and approached the anaerobic metabolic threshold with a maximum of 1.7 times the resting earlobe blood flow, but decreased quickly after exercise.

Key words: Cardiopulmonary exercise test, Hemodynamics, Flowmeters

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INTRODUCTION

In the clinical setting, the cardiopulmonary exercise test (CPET) is used to evaluate exercise tolerances. This involves analyzing electrocardiograms, blood pressures (BP), oxygen uptakes (VO_2), and carbon dioxide outputs during incremental exercises. Peak VO_2 and anaerobic metabolic threshold (AT) are used as exercise tolerances indices. Peak VO_2 is considered a factor of life prognosis in heart disease[1, 2] and is related to the aerobic capacity of skeletal muscle. The prognosis of patients with heart disease can be enhanced by improving the aerobic capacity of skeletal muscle using exercise therapy[3]. AT is also a conversion point for energy metabolism during exercise and is used for exercise prescription in patients with cardiac disease. However, peak VO_2 and AT are comprehensive indices of respiration, circulation, and metabolism; they do not reflect only peripheral tissue perfusion.

During exercise, blood flow redistribution occurs, increasing blood flow to skeletal muscles, which demand high oxygen, and restricting blood flow to inactive muscles and gastrointestinal tract, etc[4]. Although the skin has a low oxygen demand during exercise, it increases to about twice the resting level during maximal exercise due to its role in heat dissipation[4]. The deprivation of blood flow between skin and skeletal muscle easily outweighs cardiac pump function, and exercise-induced

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reductions in stroke volume inhibit the cutaneous vasodilatory response to maintain blood pressure[5)]. Skin blood flow during exercise may indicate a reserving capacity for blood flow redistribution.

A new compact wireless laser Doppler flowmeter (LDF) has been developed. This instrument has made it possible to measure real-time skin blood flow at rest and during exercise[6, 7)]. Iwasaki et al. measured skin blood flow in healthy males while running on a treadmill at three different speeds (6 km/h, 8 km/h, and 10 km/h) and succeeded in measuring stable blood flow with few motion artifacts[8)]. In particular, earlobe blood flow (EBF) is thought to reflect peripheral tissue perfusion without the influence of respiratory or metabolic systems, as no subcutaneous tissue requires exercise-associated oxygen consumption. However, EBF behavior during CPET have not been sufficiently studied.

This study aimed to analyze EBF behavior during CPET in healthy individuals and to identify differences in peripheral tissue perfusion and energy metabolism conversion point (AT) during exercise.

PARTICIPANTS AND METHODS

The study design was a cross-sectional observational study. This study included 25 healthy males (age 23.6 ± 2.5 years, weight 64.0 ± 8.1 kg, height 171.3 ± 6.0 cm, body mass index 21.8 ± 2.4). Individuals with an orthopedic history, those with neurological symptoms, and those in whom EBF could not be properly measured were excluded. The review board of Akita University Hospital approved this study (No. 2030), and written informed consent for the collection and use of data was obtained from all participants by the Declaration of Helsinki.

All tests were performed on a cycle ergometer (AEROBIKE 75XLIII, COMBI WELLNESS, Tokyo, Japan) according to the methodology reported in a previous study[9)]. The examination room was maintained at 22–26°C and 40–60% humidity. VO^2 was measured using the bless by bless method with a gas analyzer (Aeromonitor AE-310, Minato Medical Science, Osaka, Japan). During the tests, continuous 12-lead electrocardiographic monitoring and BP measurements were performed every 60 s. The test began with 4 min of rest and a 4 min 20 W warm-up (W/U), followed by a continuous 2 W increase in the work rate every 6 s. Participants were instructed to maintain cadences at 60 rpm. The test was carried out until participants reached exhaustion (peak), followed by 2 min of cool-down (C/D) and 4 min of rest (Recovery). AT were determined using the V-slope or trend method with the consensus of two experienced specialists (a cardiologist and a physical therapist).

EBF during CPET was measured using a wireless LDF (POCKET LDF, JMS, Tokyo, Japan). The participants wore the sensor probe attached with a clip on their left earlobe. The sampling frequency of the EBF waveform was 50 Hz. The measured values, transferred via a Bluetooth system, were recorded on a personal computer equipped with specially developed data acquisition software[6)]. We measured EBF as a moving average every 5 s. Since EBF was affected by the thickness of the earlobe and the number of capillaries, we calculated the %change of EBF from the value of the rest 3 min. For analysis, we plotted relative EBF every 10% of peak exercise intensity (%$\text{Load}_{\text{peak}}$) during incremental exercise. The EBF inflection point was determined as the first point at which the slope of the EBF waveform changes during incremental exercise load with the consensus of the two specialists (a cardiologist and a physical therapist).

Data are presented as mean ± standard deviation (SD). The %change of EBF during the incremental exercise test was compared with the EBF at rest using the Bonferroni method. The relationships between the %change of EBF and that of hemodynamic parameters were determined using Pearson's correlation coefficients.

Furthermore, the EBF inflection point was determined via piecewise regression. A moving average was used as a preliminary step to remove noise from the EBF data. Of the calculated points, the point that fulfilled the following three conditions was determined as the final EBF inflection point: 1. during the incremental exercise load phase, 2. EBF both before and after the change point were increasing, and 3. the change point at the earliest stage in which the above conditions were fulfilled, and the percentage relative to $\text{Load}_{\text{peak}}$ was calculated. A paired t-test was used to compare the EBF inflection point and exercise intensity of the AT. The R software was used for statistical analyses, and the significance level was 5.0%.

RESULTS

All participants completed the incremental load test. We could measure BP at AT and peak in 21 out of 25 participants. The CPET parameters are listed in Table 1. The AT point was 64.4 ± 9.8% $\text{Load}_{\text{peak}}$. The mean respiratory exchange ratio (R) at peak was 1.2 ± 0.1, and only 4 participants had values <1.1.

Figure 1 shows the typical EBF during CPET. EBF began to increase significantly from 60% $\text{Load}_{\text{peak}}$ and increased to 1.70 times the rest at peak (Fig. 2). After the exercise, EBF decreased rapidly. EBF 6 min after the incremental exercise load test was 1.25 times higher than at rest. There were no significant correlations between the %change of EBF and that of hemodynamic parameters (Table 2). The EBF inflection point by piecewise regression was 36.4% $\text{Load}_{\text{peak}}$, significantly lower than the AT 58.1% $\text{Load}_{\text{peak}}$ ($p<0.001$) (Fig. 3).

DISCUSSION

The result of the present study showed the change in EBF during CPET in healthy males. EBF significantly increased from 50% $\text{Load}_{\text{peak}}$ and reached up to 1.7 times that at rest at peak. After the exercise, EBF decreased rapidly. We determined that

Table 1. Results of CPX and LDF measurements[a]

	Rest	W/U	AT-1 min	AT	Peak
Time (sec)	180 ± 0.0	360 ± 0.0	720 ± 67.8	780.0 ± 67.8	976.5 ± 86.2
Load (W)	0.0 ± 0.0	20.0 ± 0.0	102.9 ± 19.6	122.9 ± 19.6	190.5 ± 28.7
%Load$_{peak}$ (%)	0.0 ± 0.0	11.2 ± 1.4	53.2 ± 9.2	64.4 ± 9.8	100.0 ± 0.0
HR (/min)	70.3 ± 9.8	84.7 ± 9.0	116.0 ± 12.7	127.1 ± 13.0	170.7 ± 11.4
SBP (mmHg)	115.3 ± 12.6	119.0 ± 5.8	128.8 ± 20.1	134.1 ± 26.2	143.5 ± 23.0
DBP (mmHg)	77.0 ± 7.6	75.5 ± 11.5	75.6 ± 17.7	77.0 ± 9.0	79.0 ± 15.1
PP (mmHg)	38.3 ± 9.9	43.6 ± 11.7	53.2 ± 29.2	57.1 ± 26.9	64.5 ± 25.8
MAP (mmHg)	89.7 ± 8.3	90.0 ± 8.3	91.7 ± 13.7	96.0 ± 11.0	100.5 ± 13.4
VO$_2$ (ml/min/kg)	3.9 ± 0.3	8.3 ± 0.5	17.6 ± 4.2	20.2 ± 4.8	31.3 ± 8.4
R	0.90 ± 0.1	0.90 ± 0.1	1.0 ± 0.1	1.0 ± 0.1	1.2 ± 0.1
RR (/min)	15.0 ± 3.4	19.6 ± 3.4	21.9 ± 3.6	22.0 ± 3.9	31.0 ± 7.5
VE (l/min)	9.3 ± 1.2	16.9 ± 2.0	29.6 ± 6.3	32.7 ± 6.5	63.4 ± 18.7

[a]Values are expressed as mean ± standard deviation.

CPX: cardiopulmonary exercise test; LDF: laser doppler flowmeter; Load$_{peak}$: peak exercise intensity; HR: heart rate; SBP: systolic blood pressure; DBP: diastolic blood pressure; PP: pulse pressure; MAP: mean blood pressure; VO^2: oxygen uptake; RR: respiratory rate; VE: minute ventilation.

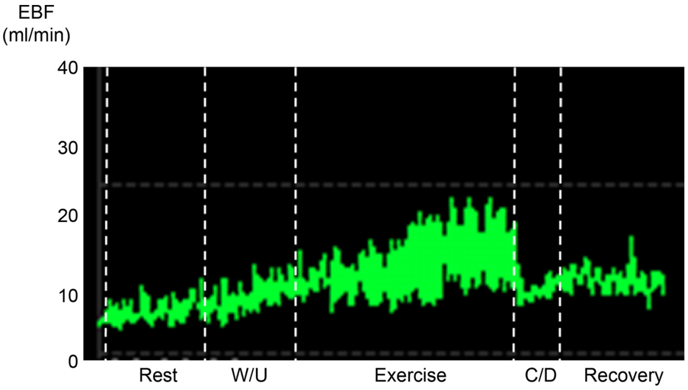

Fig. 1. Typical pattern of earlobe blood flow during incremental exercise load (Actual measurement display).
EBF: earlobe blood flow; C/D: cool-down; W/U: warm-up.

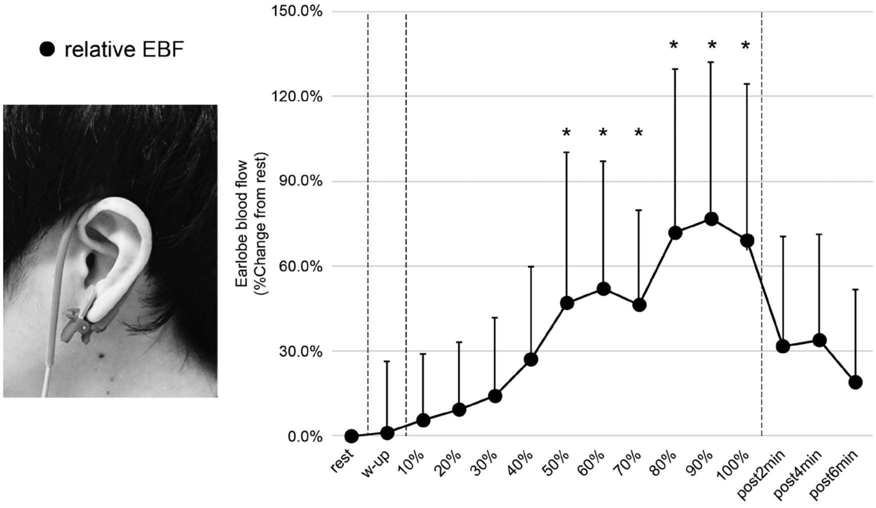

Fig. 2. Changes in the relative earlobe blood flow (ratio to rest) during incremental exercise load.
*: significant differences between the values at rest, $p<0.05$.
EBF: earlobe blood flow.

Table 2. Correlation between the rate of change of EBF and that of hemodynamic parameters (from rest to peak)

	r
HR%	−0.377
SBP%	−0.020
DBP%	−0.138
PP%	−0.037
MAP%	−0.057

*: Significant correlation, $p<0.05$.
Pearson's correlation coefficient.
HR: heart rate; SBP: systolic blood pressure; DBP: diastolic blood pressure; PP: pulse pressure; MAP: mean blood pressure.

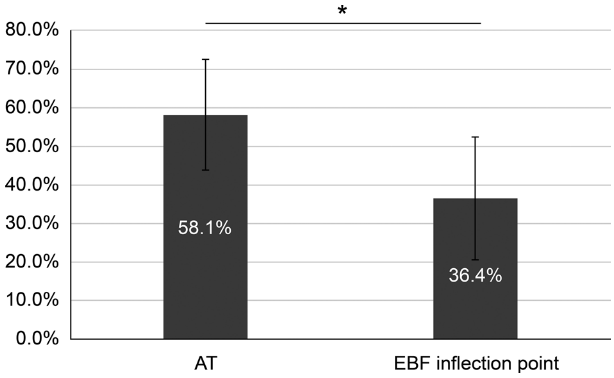

Fig. 3. Comparison between EBF inflection point and AT.
*: significant differences between the %Load$_{peak}$ at the EBF inflection point and AT, $p<0.001$.
AT: anaerobic metabolic threshold; EBF: earlobe blood flow; %Load$_{peak:}$ % of peak exercise intensity.

CPET in this study applied a sufficient load for peak because the AT point was consistent with previous studies (almost 60% Load$_{peak}$), and R values at peak were >1.1[9)].

The skin blood flow at peak exercise increases about 2.0 times compared with those values at rest[4)]. A study measuring the forearm skin blood flow using LDF reported a gradual increase in skin blood flow during lower limb exercise and an immediate decrease after the end of exercise[10)]. Another study that measured blood flow in the brachial and femoral arteries during incremental exercise load using Doppler ultrasonography reported a significant increase in blood flow in both arteries from 60% Load$_{peak}$[11)]. In a study that measured the external carotid artery blood flow by three different exercise intensities, the external carotid artery blood flow increased significantly from 40% of the maximal exercise intensity and increased more steeply from 60% to 80% Load$_{peak}$[12)].

Furthermore, the external carotid artery blood flow increased significantly between 60% Load$_{peak}$ and 80% Load$_{peak}$[12)]. In other words, the external carotid artery perfusing the earlobe showed a two-step upward response at moderate and high exercise intensities, different from that of the brachial artery perfusing the forearm. In the present study, EBF increased in response to exercise load and showed a two-step ascending response similar to the external carotid artery. While the rate of increase in EBF remained the same, the blood flow in the external carotid artery showed a steeper increase from 60% Load$_{peak}$ to 80% Load$_{peak}$ in the previous study. The rate of increase in skin blood flow decreases during high-intensity exercise to ensure muscle blood flow. In other words, EBF reflected the blood flow in the external carotid artery up to 60% Load$_{peak}$ and was considered to be influenced by the skin's vascular response at higher intensities. Since characteristics of the change in EBF during the CPET show a similar pattern to those in previous studies, our results of this instrumentation are considered valid. These findings suggest that EBF may be affected by the external carotid artery and show a specific response that differs from the extremities.

The EBF inflection point was associated with AT. Seki et al. have developed an AT-determining device using the lactate threshold in sweat since sweat and blood lactate levels increase after AT[13)]. Sweating and increased skin blood flow during exercise are skin functions with the common purpose of dissipating body heat. Skin vasodilation hyperactivity due to body heat dissipation is a sympathetic nerve reaction to skin blood flow during exercise[14)]. In the early phase of exercise, "passive vasodilation" occurs, in which skin vessels dilate and blood flow increases. When the temperature rises, skin blood flow is increased by "active vasodilation", which occurs due to the activation of cholinergic sympathetic nerves.

Parasympathetic nerve activity gradually decreases from the beginning of exercise to AT, and sympathetic nerve activity increases after AT[15]. Since the earlobe has little sympathetic innervation, it was interpreted that the effects of sympathetic nerve activity appeared strongly after AT, when parasympathetic nerve activity decreased. From what has been discussed above, it seems reasonable to interpret that the increase in EBF after AT point reflects the enhancement of skin vasodilatory response due to sympathetic nerve activity.

EBF during exercise provides us with new information about local circulation. The simple observation is that with low levels of exercise, there is an increase in EBF, which might be a simple consequence of increased blood pressure. This alone might be sufficient to test the response of peripheral circulation and may show deficits in patients with cardiovascular diseases. As exercise intensity increases, the number of factors influencing EBF increases, including autonomic innervation and thermoregulatory responses. The peripheral arteries in patients with heart failure are often contracted by sympathoexcitation. This causes poor circulation in the peripheral tissues, and exercise may cause more sympathoexcitation. Patients with heart failure often experience sympathoexcitation[16], leading to the contraction of peripheral arteries, which results in poor circulation in the peripheral tissues. Additionally, exercise may exacerbate sympathoexcitation[17]. Therefore, it can be expected that EBF during the CPET may show abnormal changes in patients with heart failure. Based on the pattern of EBF changes in the CPET revealed in this study, abnormal patterns can be discerned.

Our study had several limitations. First, we did not measure the body core or skin temperature. The skin blood flow during exercise is affected by the core temperature[18] and can function as a radiator[19]. Therefore, EBF may have increased heat dissipation during the latter half of the exercises, but could not be mentioned in this study. Second, we could not investigate the influence of gender and age-related differences. Third, we did not measure autonomic nerve activity. Future studies are needed to understand the relationship between EBF and autonomic activity during exercise.

This study measured the EBF during CPET in young, healthy males. EBF increased from 50% $\text{Load}_{\text{peak}}$ (near AT) to 1.7 times that at peak and immediately decreased after exercise. The findings of this study provide the insight needed to discriminate abnormal EBF patterns during exercise. The EBF during CPET might be sufficient to test the response of peripheral circulation and may show deficits in patients with cardiovascular diseases.

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Conflict of interest

There are no conflicts of interest to declare.

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REFERENCES

1) Mancini DM, Eisen H, Kussmaul W, et al.: Value of peak exercise oxygen consumption for optimal timing of cardiac transplantation in ambulatory patients with heart failure. Circulation, 1991, 83: 778–786. [Medline] [CrossRef]
2) Shin SY, Park JI, Park SK, et al.: Utility of graded exercise tolerance tests for prediction of cardiovascular mortality in old age: the Rancho Bernardo Study. Int J Cardiol, 2015, 181: 323–327. [Medline] [CrossRef]
3) Jondeau G, Katz SD, Zohman L, et al.: Active skeletal muscle mass and cardiopulmonary reserve. Failure to attain peak aerobic capacity during maximal bicycle exercise in patients with severe congestive heart failure. Circulation, 1992, 86: 1351–1356. [Medline] [CrossRef]
4) McArdle EM, Katch FI, Katch VL: Exercise physiology: nutrition energy, and human performance, 2nd ed. Philadelphia: Wolters Kluwer, 1992.
5) Rowell LB: Human circulation. In: Circulatory adjustments to dynamic exercise and heat stress: competing controls. New York: Oxford University Press, 1986, pp 363–406.
6) Kimura Y, Goma M, Onoe A, et al.: Integrated laser Doppler blood flowmeter designed to enable wafer-level packaging. IEEE Trans Biomed Eng, 2010, 57: 2026–2033. [Medline] [CrossRef]
7) Goma M, Kimura Y, Shimura H, et al.: Orthostatic response of cephalic blood flow using a mini laser Doppler blood flowmeter and hemodynamics of a new active standing test. Eur J Appl Physiol, 2015, 115: 2167–2176. [Medline] [CrossRef]
8) Iwasaki W, Nogami H, Takeuchi S, et al.: Detection of site-specific blood flow variation in humans during running by a wearable laser Doppler flowmeter. Sensors (Basel), 2015, 15: 25507–25519 [CrossRef]. [Medline]
9) Adachi H: Cardiopulmonary exercise test. Int Heart J, 2017, 58: 654–665. [Medline] [CrossRef]
10) Johnson JM, Rowell LB: Forearm skin and muscle vascular responses to prolonged leg exercise in man. J Appl Physiol, 1975, 39: 920–924. [Medline] [CrossRef]
11) Tanaka H, Shimizu S, Ohmori F, et al.: Increases in blood flow and shear stress to nonworking limbs during incremental exercise. Med Sci Sports Exerc, 2006, 38: 81–85. [Medline] [CrossRef]

12) Sato K, Ogoh S, Hirasawa A, et al.: The distribution of blood flow in the carotid and vertebral arteries during dynamic exercise in humans. J Physiol, 2011, 589: 2847–2856 [CrossRef]. [Medline]

13) Seki Y, Nakashima D, Shiraishi Y, et al.: A novel device for detecting anaerobic threshold using sweat lactate during exercise. Sci Rep, 2021, 11: 4929. [Medline] [CrossRef]

14) Rowell LB: The cutaneous circulation. In: Physiology and biophysics II circulation, respiration, and fluid balance. Philadelphia: Saunders Company, 1974, pp 185–199.

15) Yamamoto Y, Hughson RL: Coarse-graining spectral analysis: new method for studying heart rate variability. J Appl Physiol, 1991, 71: 1143–1150. [Medline] [CrossRef]

16) Middlekauff HR: Making the case for skeletal myopathy as the major limitation of exercise capacity in heart failure. Circ Heart Fail, 2010, 3: 537–546. [Medline] [CrossRef]

17) Coats AJ, Clark AL, Piepoli M, et al.: Symptoms and quality of life in heart failure: the muscle hypothesis. Br Heart J, 1994, 72: S36–S39. [Medline] [CrossRef]

18) Johnson JM, Proppe DW: Cardiovascular adjustment to heat stress. In: Handbook of physiology. Section 4: Environmental Physiology, vol. I. New York: Oxford University Press, 1996, pp 215–243. [CrossRef].

19) Johnson JM: Nonthermoregulatory control of human skin blood flow. J Appl Physiol, 1986, 61: 1613–1622. [Medline] [CrossRef]