

The Effects of Artificial Carbon Dioxide Foot Bathing on the Skin of Ischemic Feet, as Measured by a Laser Doppler Flowmeter

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Introduction

Carbon dioxide bathing, including foot bathing, has long been used for therapeutic purposes in Europe and elsewhere. Yet, much remains unknown about its precise physiological effects, and very few basic or clinical studies have been conducted to date. We previously reported that the optimum free carbon dioxide concentration and the optimum water temperature in an artificial CO₂ foot bath differ between healthy adults and elderly patients [2]. Given the high frequency among the elderly of peripheral circulatory disorders with associated ischemia (ischemic extremities) due to peripheral arterial occlusion in the lower extremities which can cause functional disorders of the feet [2], we surmised from our earlier investigation that a carbon dioxide concentration of at least 700 ppm and a bath temperature of at least 34°C are effective for increasing blood flow.

In the present study, we have examined the effects of artificial carbon dioxide foot bathing on ischemic feet by measuring cutaneous blood flow. We have also investigated the reproducibility of the effects of foot bathing on blood flow in ischemic feet. The results from both investigations are presented here.

Subjects

1. Cutaneous Blood Flow Study:

Nine patients with ischemic feet due to chronic peripheral arterial occlusive disorders served as the subjects of the study. Eight of the patients were male, and one was female. The average age at the time of the study was 67 years. According to the Fontaine classification of clinical symptoms, all nine cases were Fontaine stage II. The average ankle-brachial pressure index (ABPI) was 0.6.

2. Reproducibility Study:

This study was conducted on the affected foot in all nine patients described above. A related study was also conducted on the affected foot in two other patients with foot symptoms such as an abnormal sensation of cold (psychroesthesia) who were able to undergo foot bathing at least twice at intervals of several days. The latter patients were both male and had an average age of 50 years.

Method

1. Cutaneous Blood Flow:

Artificial carbon dioxide-containing water for foot bathing was generated using a CO₂-enriched water production unit [1] manufactured by Mitsubishi Rayon Engineering Co., Ltd. The carbon dioxide concentration was set at about 900 to 1,000 ppm, and the water temperature was set at 37°C (see Fig. 1).

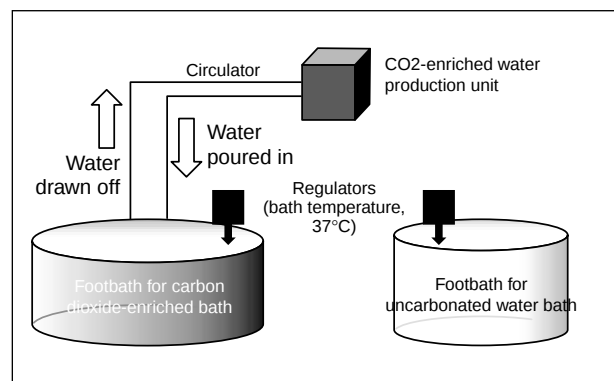


Fig. 1. Schematic of carbon dioxide-enriched foot bath.

To keep the carbon dioxide concentration constant during foot bathing, a water-circulating circuit was installed which produces carbon dioxide-enriched water and which repeatedly pours CO₂-enriched water into the

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footbath and at the same time draws off water from the bath to be CO₂-enriched, thereby effecting the circulation of carbonated water. In addition, a regulator was used to keep the bath temperature constant.

A warm water bath having the same bath temperature of 37°C but containing ordinary, uncarbonated water was used as the control. The bath temperature was similarly held constant using a regulator.

Observations collected during the study were (1) changes in subjective symptoms (e.g., sense perceptions in both feet, state of consciousness, respiratory state), determined by directly questioning the patient, and (2) cutaneous blood flow. To obtain the latter, the water-resistant probe of a laser Doppler flowmeter (ALF 2100, manufactured by Advance Co., Ltd.) was secured with adhesive tape (adjusted using a weighted spacer to a distance of 1 mm from the skin surface) to the upper surface of the affected foot in order to enable continuous measurement of cutaneous blood flow at the same site. A recording device was used to continuously record blood flow. The blood flow was averaged over time at fixed intervals during measurement so as to generate averages of continuously recorded values, and the blood flows during fresh (non-carbonated) water baths and carbon dioxide baths were statistically compared (paired t-test).

The procedure consisted of having the subject sit in a chair and remain at rest for about 10 minutes, then completely immersing the affected foot in water within a footbath. First, the foot was bathed in a warm freshwater bath for 5 minutes (a), after which it was similarly bathed for 5 minutes in CO₂-enriched water (b). Above operations (a) and (b) together constituted a single “course.” Two courses were repeated, and the change in cutaneous blood flow each time was continuously recorded (over a total period of 25 minutes).

To evaluate also the “water circulation effects” of drawing off and reintroducing the CO₂-enriched water, during the second carbon dioxide foot bath, six of the subject feet in the study were bathed for 5 minutes with the circulator turned off (that is, in bathwater at rest) and the cutaneous flow rate was measured. Using a paired t-test, the results were compared with the results obtained with the circulator on.

2. Reproducibility:

Reproducibility in this study was determined from the results obtained by repeating the same set of operations twice. In addition, the reproducibility of the difference in results for carbon dioxide bathing and freshwater bathing (both at 37°C) was also examined to see if the same pattern of relative results occurred when the procedure was carried out on a different day. The procedure used and the type of data collected were the same as in the cutaneous blood flow study described above. That is, the subject was made to sit in a chair and remain at rest for about 10 minutes, following which the affected foot was completely immersed in a footbath and bathed 5 minutes in warm uncarbonated water then bathed 5 minutes in CO₂-enriched water (these two steps together constituting a single course). The continuously measured cutaneous blood flow obtained in each of two such courses was examined to determine the “same-day reproducibility.” This was supplemented by a “different-day reproducibility” study in which the subjects were administered foot baths as described above a first time, following which the same procedure was repeated several days later on the same patient.

Ethical Considerations:

Prior to the investigation, the subjects were given a full explanation of the purpose of the study, the procedure, and the possible effects of treatment to be administered. Informed consent was obtained from each patient.

Results

1. Cutaneous Blood Flow:

Cutaneous blood flow rose slightly in the first freshwater foot bath, whereas it showed a significant rise after 2–3 minutes in the first CO₂-enriched foot bath. With subsequent immersion in a freshwater bath (second course), the blood flow returned to about the same level as during the freshwater bath in the first course. Moreover, the cutaneous blood flow from foot bathing with CO₂-enriched water in the second course rose after 2–3 minutes, just as it had in the first course. As shown in Fig. 2, cutaneous blood flow during the carbon dioxide baths rose markedly, by a factor of about 2.6 to 2.7, relative to blood flow during the freshwater baths. Similar increases in blood flow were observed in all the subjects ($p < 0.01$, see Table 1).

Next, in the study conducted to determine the effects

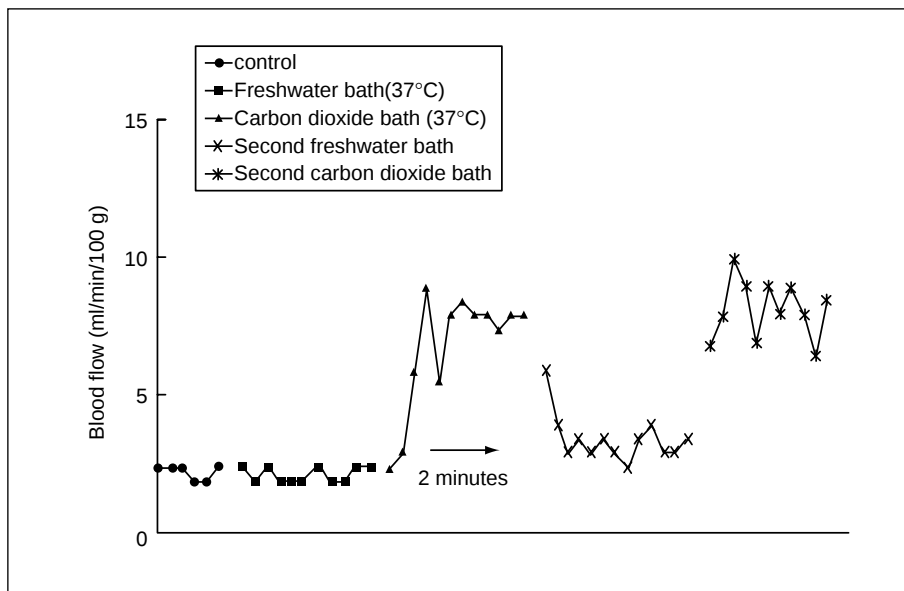


Fig. 2. Change in cutaneous blood flow during foot bathing (70-year-old male).

Table 1. Change in cutaneous blood flow during foot baths (n=9)

	Initial value (prior to bath)	Fresh water bath	Carbon Dioxide bath	Fresh water bath	Carbon dioxide bath
Blood flow (mean $\pm$ SD)	2.6 $\pm$ 0.6	3 $\pm$ 0.8	7.5 $\pm$ 2.3	4.3 $\pm$ 1.6	7.1 $\pm$ 2.8
Intermediate value	2.5	3.1	7.4	3.5	6.8
Percent change from initial value	1	1.2	2.7	1.6	2.6

(p<0.01)

Table 2. Reproducibility of cutaneous blood flow during foot bathing (n=2)

	Initial value (prior to bath)	Fresh-water bath	Carbon dioxide bath	Fresh-water Bath	Carbon dioxide bath
First time	2.75	3.8	9.9	5.6	10.6
Second time	2	3.6	9.3	6.7	10.4

Note: Figures shown are average values for the two subjects.

of water circulation in a carbon dioxide bath, the cutaneous blood flow in the group given a foot bath with circulation, expressed as the average $\pm$ standard deviation, was 7.4 $\pm$ 2.6 ml/min/100 g. The value obtained for the group given a foot bath without circulation was 6.7 $\pm$ 3.4 ml/min/100 g. These results show that water circulation tended to result in a slightly higher blood flow, but the difference was not significant.

In the study on subjective symptoms, the subjects reported a feeling of warmth during immersion, but none complained of unpleasant sensations such as pain. Sensations of cold or numbness vanished during immersion. All subjects reported an improvement in subjective symptoms due to a sense of warmth in the foot. No constitutional symptoms were observed whatsoever.

2. Reproducibility:

As shown in Table 1, excellent reproducibility was demonstrated with the repetition of the same procedure. In a study conducted to determine the reproducibility, or absence thereof, in results obtained when the bathing procedure described above was repeated on a different day, the two subjects both showed a good increase in cutaneous blood flow from carbon dioxide foot bathing. The increases in blood flow were significant (Fig. 2). The average time interval between the two sets of foot baths was 6 days.

Changes in blood flow the first time the foot baths were carried out are shown in Fig. 3a. As noted above, cutaneous blood flow rose during the carbon dioxide baths. On subsequently returning to a freshwater bath (second course), the blood flow fell to about the same level as in the freshwater bath during the first course.

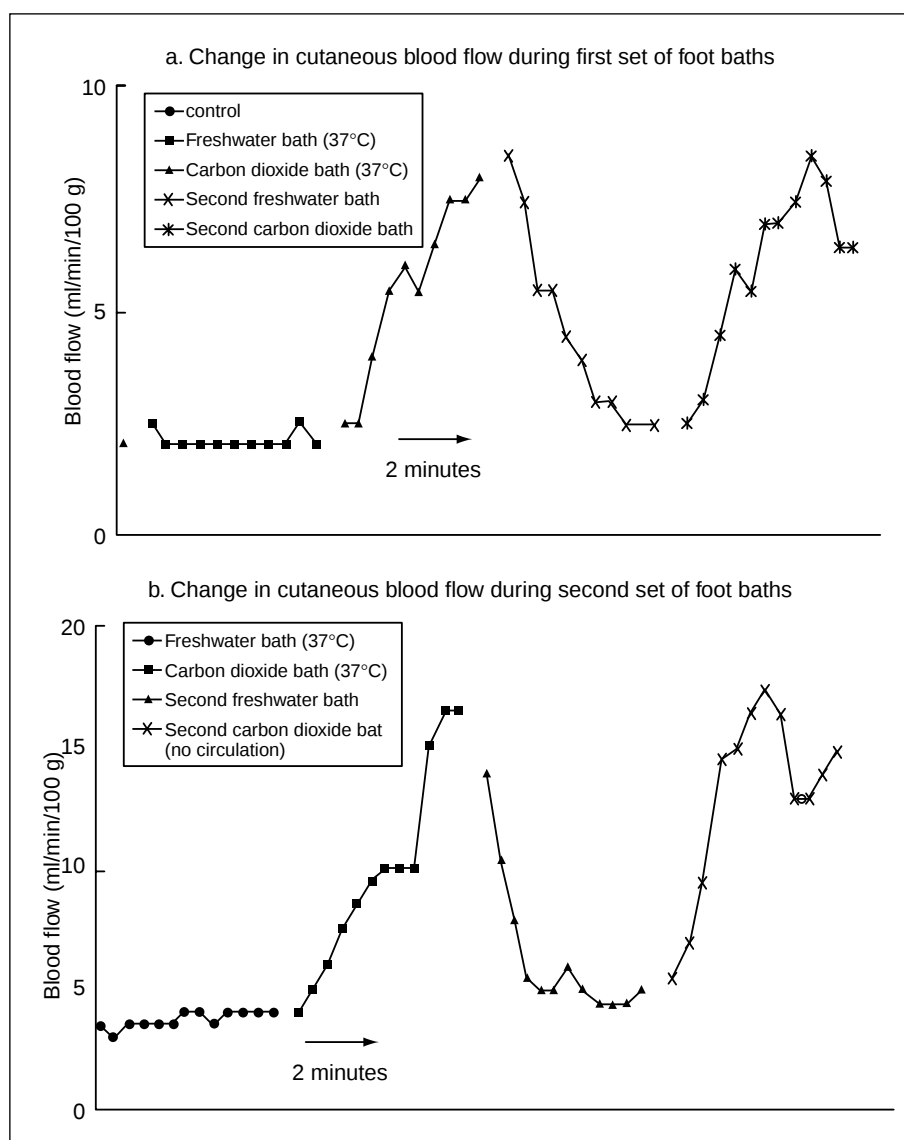


Fig. 3. Reproducibility results obtained in one patient (45-year-old male)

Blood flow during the second carbon dioxide bath rose again, just as it had during the first carbon dioxide bath.

Changes in blood flow when the set of foot baths was carried out a second time on another day are shown in Fig. 3b. Changes in cutaneous blood flow during the second set of foot baths were similar to changes that occurred during the first set of foot baths, indicating reproducibility. Results from each of the two subjects were found to show reproducibility. Improvements in subjective symptoms included disappearance in a sense of coldness and numbness of the foot, but the subjects did not note any change in general symptoms.

Discussion

Carbon dioxide absorbed percutaneously has a peripheral vasodilating effect, a cutaneous blood flow increasing effect, and a warm sensation sustaining effect. This is why it has been employed therapeutically in Europe and elsewhere for centuries ^[3,4].

Regarding the effects of carbon dioxide-containing

water, given that the optimum concentration and optimum temperature of a carbon dioxide bath differs between healthy adults and the elderly, and given also that peripheral vascular disorders are more common in the elderly, we believe that a carbon dioxide concentration of at least 700 ppm and a bath temperature of at least 34°C are effective for increasing blood flow ^[1]. However, the solubility of carbon dioxide in water at one atmosphere is 1,000 to 1,300 ppm within a water temperature range of 30–40°C ^[5], and regulations define a natural carbon dioxide spring as having a free carbon dioxide concentration of at least 1,000 mg (1,000 ppm) per kilogram of spring water ^[6]. Earlier methods were unable to artificially produce such high-concentration CO₂-containing water. However, the advent of the CO₂-enriched water production unit used in the present study now makes it possible to rapidly achieve a carbon dioxide concentration of about 1,000 ppm, and to stabilize the concentration at this level for an extended period of time.

The steady rise in the number of elderly people in Japan today has been accompanied by an increase in the incidence of arteriosclerotic disease. As a result, ischemic foot due to peripheral arterial obstructive disorders is also on the increase. Treatment methods that have commonly been used include vascular reconstruction accompanied by internal treatment ^[7]. One such method is physiotherapy, which can be employed together with kinesiotherapy, although actual use of this technique in Japan is almost nonexistent. In the present study, we used the above-described CO₂-enriched water production unit to artificially produce carbon dioxide-enriched water, and carried out carbon dioxide foot bathing as a form of thermotherapy, which is itself one type of physiotherapy, to determine whether this increases cutaneous blood flow in an ischemic foot as it does in a normal foot. Based on those results, we attempted to demonstrate whether artificial carbon dioxide foot bathing is effective as a treatment mode for ischemic feet.

In the 5-minute immersions carried out in the present study at a CO₂ concentration of about 900–1,000 ppm and a bath temperature of 37°C, the effects on the circulatory dynamics in the skin of ischemic feet were excellent, with a significant rise in cutaneous blood flow being observed in all the patients in the study. Moreover, a significant (approximately 3-fold) rise in blood flow was observed relative to the effects of freshwater baths, clearly demonstrating the greater effectiveness of a carbon dioxide bath. In this study, results from the second freshwater bath indicated somewhat of an increase in blood flow compared with the first freshwater bath. However, because these numbers were average values for a 5-minute period, the rise was most likely attributable to the lingering effects of the carbon dioxide bath that preceded it (in the present study, such effects appeared to persist for about 2 minutes), as can be seen by the gradual decline in cutaneous blood flow following transfer of the foot to a fresh water bath. This interpretation is also borne out by the fact that the intermediate values and the blood flow in the last half of the freshwater baths were very similar to the initial blood flow before the start of bathing.

To obtain a more detailed picture of the reproducibility of the carbon dioxide foot bath effects, we carried out two different procedures.

(1) A first course, consisting of a freshwater bath followed by a carbon dioxide foot bath, was followed immediately by a second identical course.

All the baths were carried out on the same day.

(2) Two courses (consisting of a total of four baths) like those described above were carried out on a single day, following which the entire set of four baths (two courses of two baths each) was repeated a second time several days later. This procedure was carried out on only two subjects.

The results obtained from both procedures showed reproducibility. Hence, we were able to conclude that the efficacy of carbon dioxide foot bathing on ischemic feet is reproducible.

In the present study, to obtain a stable and uniform carbon dioxide concentration and temperature during the short period of time in which the ischemic feet were immersed, we installed a circulator which introduced warm water having a constant carbon dioxide concentration to the footbath and at the same time drew off some of the water already in the bath. This served to achieve a uniform carbon dioxide concentration and prevented the bath from becoming too weak on account of constant circulation of the water. In the results of the present study on six subjects, the difference in blood flow attributable to the presence or absence of circulation was not statistically significant. We thus believe that a carbon dioxide foot bath of the duration carried out in the present study (5 minutes) can provide the full effects of carbon dioxide bathing without circulation of the bathwater. That is, in cases where a single batch of carbon dioxide-enriched water is produced at a constant concentration and a foot bath is carried out using this water, the effects of the bath can be fully achieved without constant circulation, so long as the bath is of short duration (up to about 10 minutes). However, the bath temperature does have to be stabilized at a constant temperature using a regulator.

The increase in cutaneous blood flow was accompanied by a reddening, or flushing, of the skin in immersed areas and by a change in subjective symptoms (sensation of warmth). The skin flushing effect in a carbon dioxide foot bath shows concentration dependence, and is thought to arise from the dilation of precapillary arterioles and capillaries. In addition, Komoto et al. have reported a rise in oxygen partial pressure, both in the skin and muscles, from carbon dioxide adaptation to the skin ^[8]. The only data collected in the present study was a rise in cutaneous blood flow, but because these results were indicative of efficacy in ischemic feet, carbon dioxide bathing can certainly be expected to have desirable effects on the skin and

muscles of ischemic feet. Bathing with carbon dioxide-enriched water thus clearly shows potential as a form of physiotherapy for ischemic feet, including cases involving, for example, sensations of cold or numbness, skin ulcers, and claudication.

Thorough investigations remain to be done on such topics as the carbon dioxide concentration and the immersion time. Bath temperature also merits further study. For example, it has been reported that even a warm freshwater bath increases blood flow, and it has been confirmed that blood flow tends to increase in accordance with the degree of rise in temperature ^[1]. Moreover, we know that the effects of a carbon dioxide bath last only a short while after the bath (several minutes in the present study), and were unable in the present study to judge the cumulative effects of two such repeated baths. There clearly exists a need to closely investigate the most effective treatment conditions for ischemic feet in connection with such factors as carbon dioxide concentration and length of immersion.

Further to the point, ischemic feet are known to occur to varying degrees of severity. One area requiring investigation is the optimum set of conditions, such as carbon dioxide concentration, temperature and immersion time in carbon dioxide water, that would make carbon dioxide bathing most effective for treatment tailored to the degree of severity, including severely ischemic feet (involving pain while at rest or ischemic ulceration) where the degree of ischemia is the highest (ABPI is 0.3 or less).

No particular constitutional symptoms were observed in the present study. However, even though the only part of the body immersed is the foot, where such treatment is administered to elderly patients—a population known to have a high incidence of disorders in general physiological function (many patients with ischemic foot are elderly), the effects of such foot bathing not only on cutaneous blood flow, as in the present study, but also on the entire body, including the heart and other vital organs, should probably be studied.

Conclusion

Artificial carbon dioxide foot bathing (CO₂ concentration, 900–1,000 ppm; bath temperature, 37°C)

significantly increased cutaneous blood flow in ischemic feet, and improved subjective symptoms. Moreover, the artificial carbon dioxide foot bath-induced rise in cutaneous blood flow in the feet was found to be reproducible. The same was true of the improvement in subjective symptoms. These results demonstrate the effectiveness of this method in the treatment of ischemic feet, and indicates its potential utility as a form of physiotherapy in the treatment of ischemic feet. Further studies need to be carried out on related topics, including optimum carbon dioxide concentration and the general effects of carbon dioxide foot bathing on the body.

References

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