Carbon Dioxide–Rich Water Bathing Enhances Collateral Blood Flow in Ischemic Hindlimb via Mobilization of Endothelial Progenitor Cells and Activation of NO-cGMP System

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Background—Carbon dioxide–rich water bathing has the effect of vasodilatation, whereas it remains undetermined whether this therapy exerts an angiogenic action associated with new vessel formation.

Methods and Results—Unilateral hindlimb ischemia was induced by resecting the femoral arteries of C57BL/J mice. Lower limbs were immersed in CO_2-enriched water (CO_2 concentration, 1000 to 1200 mg/L) or freshwater (control) at 37°C for 10 minutes once a day. Laser Doppler imaging revealed increased blood perfusion in ischemic limbs of CO_2 bathing (38% increase at day 28, $P<0.001$), whereas N^G-nitro-L-arginine methyl ester treatment abolished this effect. Angiography or immunohistochemistry revealed that collateral vessel formation and capillary densities were increased (4.1-fold and 3.7-fold, $P<0.001$, respectively). Plasma vascular endothelial growth factor (VEGF) levels were elevated at day 14 (18%, $P<0.05$). VEGF mRNA levels, phosphorylation of NO synthase, and cGMP accumulation in the CO_2-bathed hindlimb muscles were increased (2.7-fold, 2.4-fold, and 3.4-fold, respectively) but not in forelimb muscles. The number of circulating Lin−/Flk-1+/CD34− endothelial-lineage progenitor cells was markedly increased by CO_2 bathing (24-fold at day 14, $P<0.001$). The Lin−/Flk-1+/CD34− cells express other endothelial antigens (endoglin and VE-cadherin) and incorporated acetylated LDL.

Conclusions—Our present study demonstrates that CO_2 bathing of ischemic hindlimb causes the induction of local VEGF synthesis, resulting in an NO-dependent neocapillary formation associated with mobilization of endothelial progenitor cells. (***Circulation*. 2005;111:1523-1529.**)

Key Words: carbon dioxide ■ hypercapnia ■ angiogenesis ■ stem cells ■ endothelium ■ vasculogenesis

Carbon dioxide–rich (CO_2) water bathing has a long history and is thought to be effective in the treatment of peripheral vascular disorder[1]; however, the mechanism(s) underlying this traditional therapy remains poorly defined. The effect of CO_2-enriched water on cutaneous circulation depends primarily on the vasodilatation elicited by the CO_2 that diffuses into the subcutaneous tissue through the skin layers.[2,3] Findings in the intact coronary circulation[4] and in isolated aortic strips[5] have suggested that vasodilation in response to CO_2 may be mediated in part by nitric oxide (NO).

Previous investigations have provided inferential evidence that biological processes modulated by NO might extend to include angiogenesis. Direct in vitro evidence that NO may induce angiogenesis was demonstrated recently by Papapetropoulos et al.[6,7] Ziche et al[8,9] established the first line of evidence that NO can induce angiogenesis in vitro. Murohara et al[10] clearly showed NO-mediated angiogenesis in response to tissue ischemia in NO-deficient mice. We have also reported that overexpression of endothelial NO synthase (eNOS) causes a marked increase in neocapillary formation in response to tissue ischemia.[11] Furthermore, hypercapnia-associated acidosis was reported to induce the expression of angiogenic factors, vascular endothelial growth factor (VEGF), or basic fibroblast growth factor and inhibit endothelial cell apoptosis.[12] Taken together, this accumulated evidence may raise the possibility that the CO_2-enriched water bathing therapy enhances regional blood perfusion by increasing new vessel formation. In the present study, we report that CO_2-enriched water bathing stimulates blood flow restoration in the ischemic hindlimbs of mice by increasing NO-dependent collateral vessel formation and the mobilization of endothelial-lineage progenitor cells into the circulation.

Methods

Principle of the Device

This device uses a CO_2 gas–permeable membrane similar to the principle of an artificial lung on the extracorporeal circulatory system. The unit consists of 15 000 multilayered composite-membrane hollow fibers with porous membrane sandwiching on

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both sides of gas-permeable membrane (Mitsubishi-Leiyon) and is capable of instantly converting 20 L/min of water (pH 7.0) into CO_2-enriched water (free CO_2 concentration, 1000 to 1200 mg/L, pH 5.0).

Mouse Model of Unilateral Hindlimb Ischemia and CO_2 Bathing

Unilateral hindlimb ischemia was induced by resecting the right femoral arteries (including muscle branches) and veins of 8-week-old male C57BL/J mice under anesthesia with sodium pentobarbital (50 mg/kg IP).[11,13] To inhibit NOS chronically, the mice were provided water containing 1 mg/mL N^G-nitro-L-arginine methyl ester (L-NAME) for 4 weeks.[11] Because CO_2 bathing immediately after operation delayed the closure of this skin wound, we started the CO_2 bathing of the lower limb from 4 days after surgery. Lower limbs of mice were immersed into CO_2-enriched water for 10 minutes or freshwater (control) at 37°C once a day under anesthesia (n=10 in each group). The Institutional Animal Care and Use Committee of our university approved all animal protocols.

Immunohistochemistry

Four pieces of ischemic tissues from the adductor and semimembranous muscles were obtained 28 days after the surgery of hindlimb ischemia. Frozen sections were stained with anti-factor VIII, followed by incubation with TRIC-conjugated secondary antibody. Five fields from 2 muscle samples of each animal were randomly selected for capillary counts. To ensure that capillary densities were not overestimated as a consequence of myocyte atrophy or underestimated because of interstitial edema, the capillary/muscle fiber ratio was determined.[11,13] To examine whether cells survived in the tissues, adjacent sections were subjected to alkaline phosphatase staining by the indoxyl-tetrazolium method. Alkaline phosphatase staining turns capillary endothelial cells a dark blue color only when they are viable and when the intracellular enzyme activity remains intact.[11,13]

Laser Doppler Analysis and Angiography

We measured the ratio of the ischemic (right)/normal (left) limb blood flow by use of a laser Doppler perfusion image (LDPI) analyzer (Moor Instruments). After blood flow had been scanned twice, stored images were subjected to computer-assisted quantification of blood flow, and average flows of the ischemic and nonischemic limbs were calculated. To minimize data variables caused by ambient light and temperature, the LDPI index was expressed as the ratio of ischemic (left) to nonischemic (right) limb blood flow.[11,13]

Vessel density was evaluated with a microfocus x-ray television device (Hitex Co Ltd) 28 days after ischemia (n=5). Longitudinal laparotomy was performed to introduce a catheter into the abdominal aorta, followed by injection of contrast medium (lipiodol). Angiography was performed for 2 seconds after the injection. We quantitatively analyzed collateral vessel numbers as previously reported.[11,13] Briefly, numbers of vessels in the thigh area were counted by use of 5-mm^2 grids by 2 radiologists who were unaware of the group identity of the angiographic film. Interobserver variation was <5%.

cGMP Assay and Measurement of Blood pH Level

The assay for tissue cGMP was performed by use of the cGMP enzyme immunoassay system (Biotrak; Amersham) as previously described.[11] The tissues remaining after cGMP measurement were digested by use of a bicinchoninic acid protein assay kit (Pierce). Blood pH levels were measured by automated blood gas analyzer (ABL505, Radiometer A/S).

Northern and Western Blotting and Plasma VEGF Measurement

Frozen skeletal samples from hindlimbs or forelimbs were homogenized in Trizol reagent (Gibco BRL). Blots were hybridized with a random-primed ^{32}P-labeled cDNA probe for VEGF[11] and normalized by densities for GAPDH as an internal control. Hybridized signals were measured by scanning densitometry, and VEGF mRNA levels were arbitrarily normalized relative to the GAPDH mRNA levels.

Phosphorylation of eNOS (serine 1177) was analyzed by Western blotting using phospho-specific antibodies (New England Biolabs). The muscles were homogenized in lysis buffer. Lysates were immunoblotted with anti-phospho antibodies and detected with an enhanced chemiluminescence kit (Amersham).[11] Plasma VEGF concentration was measured by use of the ELISA kit (R&D Systems).

FACS Staining

Total nuclear cells in the peripheral blood were isolated by erythrocyte lysis with ammonium chloride solution (PharM Lyse, Becton Dickinson). Lin−/Flk+ cells were isolated by PE-labeled lineage antigens (CD11b, CD3, B220, Ter-199, Gr-1, CD4, CD8e, CD16/32), FITC-CD34, and biotin-Flk-1 and then analyzed by use of a FACScan flow cytometer.[14,15] Lin−/Flk+/endoglin+ cells were isolated by FITC-labeled lineage antigens, PE–Flk-1 and biotin-endoglin. To prove the specificity of anti-CD34 antibody, the biotin-labeled anti-mouse CD34 antibody used in this study was reacted with mouse bone marrow cells and purified with streptavidin-magnet beads, followed by fluorescence-activated cell sorter (FACS) analysis using streptavidin-PE. All anti-mouse antibodies were purchased from BD Biosciences.

Differentiation of Lin−/Flk-1+ Cells Into Endothelial Cells In Vitro

The population of Lin−/Flk-1+ cells was isolated with FACS from the peripheral blood of the mice that had undergone the limb ischemic operation and then treated with CO_2 bathing for 14 days. These cells were cultured on fibronectin-coated plastic dishes in DMEM supplemented with 100 ng/mL VEGF and 10% FBS. After 4 days, DiI-labeled acetylated LDL (Biomedical Technologies Inc) was added into medium at 2 μg/mL for 6 hours, fixed with 4% paraformaldehyde, and stained with anti–VE-cadherin antibody and FITC-labeled anti-IgG antibody.

Statistics

Statistical analyses were performed by 1-way ANOVA followed by pairwise contrasts using Dunnett's test. Data (mean±SEM) were considered significant at a value of $P<0.05$.

Results

Laser Doppler Blood Perfusion

Progressive recovery of limb perfusion was disclosed in CO_2-bathed and control freshwater-bathed mice after induction of limb ischemia. A greater degree of blood perfusion recovery was observed in the ischemic limbs of CO_2-bathed mice compared with controls (38% increase at day 28, $P<0.001$) (Figure 1, A and B). Inhibition of NOS activity by L-NAME administration abolished an enhancement of blood flow recovery by CO_2 bathing and reversed the recovery ratio toward the control level. Blood flow in L-NAME–treated mice tended to be lower than that in wild-type mice, but this difference was not significant (Figure 1B).

Angiography

All animals were subjected to iliac angiography using contrast medium (lipiodol) on postoperative day 28. Collateral vessel numbers were markedly increased in ischemic limbs of CO_2-bathed mice (4.1±0.4-fold at day 28, $P<0.001$, n=5) compared with those in water-bathed mice (Figure 2).

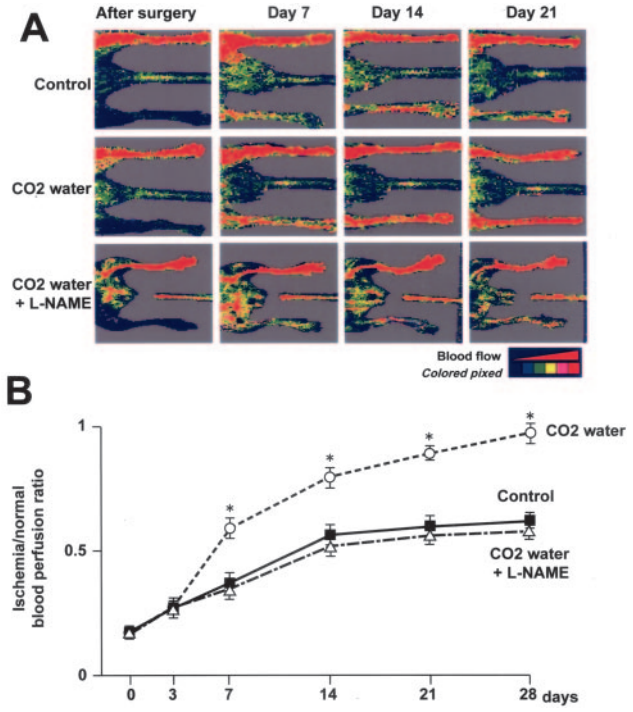

Figure 1. LDPI. A, Greater blood perfusion (red to yellow) was observed in CO_2-enriched water-bathed limbs, in contrast to reduced perfusion (green to blue) in freshwater-bathed ischemic limbs (control). B, Computer-assisted analyses of LDPI revealed significantly greater blood perfusion values in CO_2-enriched water-bathed group than in control group. Administration of L-NAME (1 mg/mL) in drinking water reduced increased perfusion by CO_2-enriched water bathing toward normal level. Values shown are mean±SEM (n=10) at each time point. *$P<0.001$ vs control mice.

Analysis of Capillary Density

Immunohistochemical staining for anti-factor VIII revealed the presence of capillary endothelial cells (Figure 3A). The capillary/muscle fiber ratio in the skeletal muscle obtained 28 days after hindlimb ischemia was significantly increased in the CO_2-bathed mice (3.7-fold, $P<0.001$) compared with that in water-bathed mice. A similar increase (4.2-fold increase, $P<0.001$) was also observed in ALP staining for detection of viable endothelial cells (Figure 3B). Administration of L-NAME (1 mg/mL) in drinking water reduced the increased vessel numbers by CO_2 bathing toward the normal level (Figure 3).

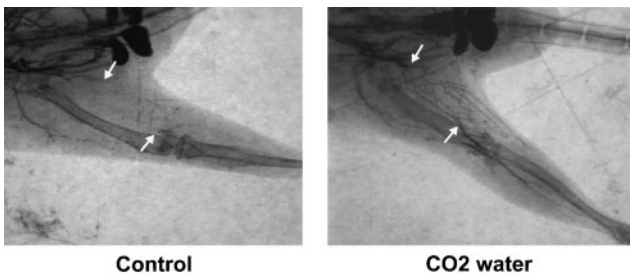

Figure 2. Angiographic analysis. Representative angiograms were obtained on postoperative day 28. Arrows indicate ligated ends of femoral arteries. Collateral vessel numbers counted by use of 5-mm^2 grids were markedly increased in ischemic limbs of CO_2-bathed mice (4.1±0.4-fold at day 28, $P<0.001$, n=5) compared with those in water-bathed mice.

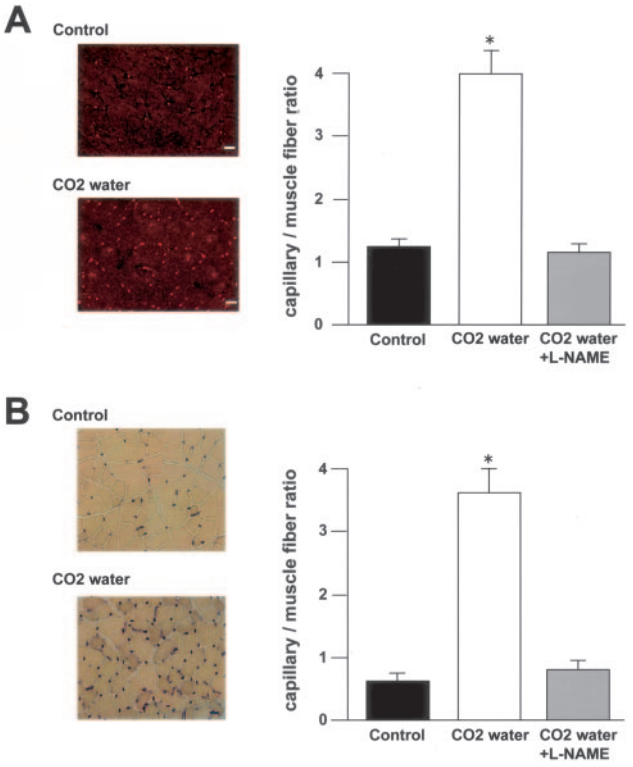

Figure 3. Immunohistochemical analysis. A, Ischemic tissues from adductor and semimembranous muscles were obtained 28 days after surgery of hindlimb ischemia. Endothelial cells were stained with anti-factor VIII antibody, followed by incubation with TRIC-conjugated secondary antisera. B, Alkaline phosphatase staining turns viable endothelial cells blue. Five fields from 2 muscle samples of each animal (n=10) were randomly selected, and capillary density was shown as capillary/muscle fiber ratio. Administration of L-NAME (1 mg/mL) in drinking water reduced increased vessel numbers by CO_2 bathing toward control levels of freshwater-bathed ischemic limbs (n=10). *$P<0.001$ vs control mice. Bars=50 μm.

Induction of VEGF Expression, eNOS Phosphorylation, and cGMP Levels

VEGF mRNA levels were examined in hindlimb muscles dissected at days 0 (before), 1, 2, 7, 14, and 21. VEGF mRNA levels were decreased immediately after hindlimb ischemia (day 1, day 2), and then gradually reverted to the basal levels at day 7 in the control group. In the CO_2-enriched water group, a marked increase in VEGF mRNA levels was observed at day 7 (1.6-fold versus day 0 preischemic levels, $P<0.01$) and showed a peak level at ≈day 14 (2.7-fold versus day 0, $P<0.001$). Induction of the VEGF mRNA from the preischemic level was significantly higher in the CO_2 bathing group than the increase in the control group (Figure 4), whereas the increase in VEGF mRNA synthesis by CO_2 bathing was not affected by L-NAME treatment (Figure 5A).

To define whether the effect of CO_2 bathing results from systemic or local VEGF synthesis, we examined the time-dependent VEGF mRNA induction in forelimb skeletal muscles after CO_2 bathing and changes in plasma VEGF levels. The mRNA levels in forelimb skeletal muscles of CO_2-bathed

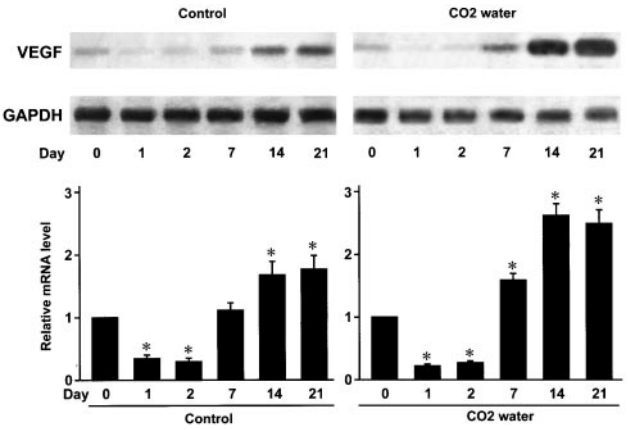

Figure 4. VEGF mRNA expression in ischemic hindlimb. Hindlimb skeletal muscles were dissected after ischemia, and RNA was extracted. Densities of VEGF mRNA signals were measured by densitometry and normalized relative to those of GAPDH mRNA signals. Results (mean±SEM, n=6) were arbitrarily indicated as values relative to VEGF mRNA levels at day 0. *$P<0.001$ vs day 0 preischemic levels.

ischemic mice did not change significantly after CO_2 bathing compared with the preischemic levels (Figure 5A). Although only induction of hindlimb ischemia did not affect plasma VEGF levels, VEGF levels in the CO_2-bathed ischemic mice were slightly but significantly elevated at day 14 (18%, $P<0.05$, n=6) compared with the water-immersed ischemic mice (n=6) (Figure 5B). Furthermore, we determined plasma pH levels to study whether CO_2 bathing–mediated effects are systemic. We found that CO_2 bathing of ischemic lower limbs did not significantly affect the pH levels in the peripheral blood (control, 7.2±0.04; CO_2 bathing, 7.2±0.03 at day 14; n=6 each). These findings demonstrate that VEGF synthesis by CO_2 bathing is induced only locally and that this increase in local VEGF synthesis leads to the elevation in plasma VEGF levels.

Skeletal muscles at day 14 (in which VEGF expression is maximally increased) were dissected, and eNOS phosphorylation and cGMP levels were examined. The eNOS phosphorylation levels at day 14 (normalized with expression levels of eNOS protein) were increased significantly in both control and CO_2-enriched water groups relative to the day 0 preischemic levels (1.6- and 2.4-fold, respectively) (Figure 6A). eNOS phosphorylation levels in the CO_2-enriched water group were significantly higher than those in the control group ($P<0.001$ versus the control group). Consistent with eNOS phosphorylation, cGMP levels in skeletal muscles at day 14 were also significantly higher (3.4-fold, $P<0.001$) in the CO_2-enriched water group compared with those in the control group (Figure 6B).

Effect of CO_2 Bathing on Circulating Endothelial-Lineage Progenitor Cells

CD34+/AC133+/Flk-1+ hematopoietic stem cells circulate in the peripheral blood of humans as an endothelial precursor cell and play a critical role in neovascularization in ischemic tissue.[16] Because AC133 marker is not available for mice, we isolated hematopoietic lineage-negative (Lin−) cells from the peripheral blood and then analyzed the CD34- and endothelial markers Flk-1– and endoglin-positive population to study whether endothelial-lineage precursor cells are mobilized by CO_2-enriched water bathing. FACS analysis indicated that Lin−/Flk-1+ cells are barely detected in the peripheral blood of normal mice (0.01±0.002% of total nuclear cells, n=12). Lin−/Flk-1+ cells were significantly increased after limb ischemia and showed a peak value at day 14 (≈7-fold versus the preischemic value) (from 0.01±0.002% to 0.073±0.002%, $P<0.001$, n=7). Interestingly, such a Lin−/Flk-1+ population was further increased by CO_2 bathing and showed a peak value at day 14 (≈24-fold increase, from 0.01±0.002% to 0.24±0.03%, $P<0.001$, n=7) (Figure 7A). The Lin−/Flk-1+ cells mobilized by CO_2 bathing were mostly positive for anti-endoglin antibody and in the CD34-negative fraction (Figure 7B). Considering that CD34−/Flk-1+ cells rather than CD34+/Flk-1+ are reported to be a real population of hematopoietic stem cells,[17] our present data

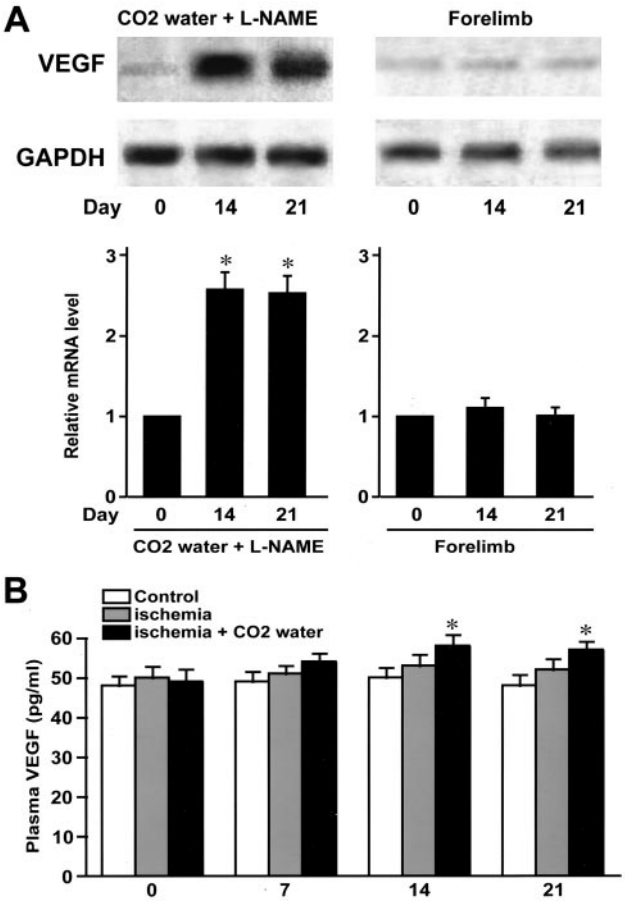

Figure 5. Effect of L-NAME on VEGF mRNA expression in hindlimb and forelimb skeletal muscles after hindlimb ischemia and plasma VEGF concentrations. A, Mice with hindlimb ischemia were provided water containing 1 mg/mL L-NAME, and time-dependent VEGF mRNA expression was measured as described in Figure 4. Forelimb skeletal muscles were dissected from hindlimb ischemia mice, and VEGF mRNA was analyzed. Results (mean±SEM, n=5) were arbitrarily indicated as values relative to VEGF mRNA levels at day 0. *$P<0.001$ vs day 0 preischemic levels, B, Plasma VEGF concentrations were measured by ELISA (control, CO_2 bathing of normal mice; ischemia, freshwater-bathed ischemic mice; ischemia+CO_2 water, CO_2-bathed ischemic mice, n=5 each). *$P<0.05$ vs day 0.

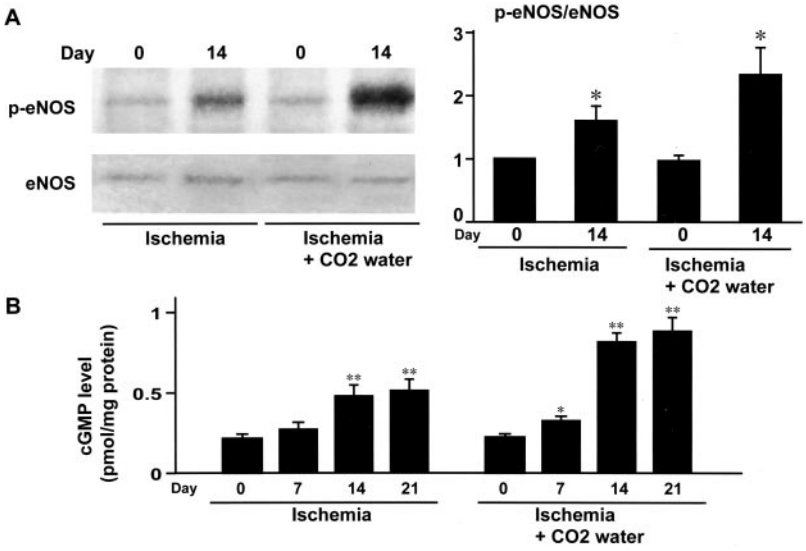

Figure 6. cGMP accumulation in ischemic limbs. A, Skeletal muscles were homogenized and immunoblotted with anti-phospho antibodies for eNOS. Phospho signals in filters were stripped and reprobed with anti-eNOS antibody. Phospho-eNOS densities were measured by densitometry and normalized relative to those of eNOS signals. Results are arbitrarily indicated as values relative to signal densities in day 0 preischemic control. Results shown are mean±SEM (n=6), and representative data are shown. *$P<0.001$ vs values in day 0 preischemic control. B, Skeletal muscles were dissected at days 7, 14, and 21 after hindlimb ischemia, and tissue cGMP levels were measured. Results shown are mean±SEM (n=6 each). *$P<0.05$, **$P<0.001$ vs day 0 preischemic control.

indicate that CO_2-enriched water bathing mobilizes very immature hematopoietic stem cells, including endothelial progenitor cells. To prove the specificity of anti-CD34 antibody, CD34+ cells were enriched by anti-mouse CD34 antibody from mouse bone marrow cells. As shown in Figure 7C, 83% purity of CD34-positive cells was detected by FACS, indicating that the staining for the CD34 antigen was properly performed.

We further examined whether Lin−/Flk-1+ cells express another endothelial marker, VE-cadherin, and also possess the characteristics of endothelial cells, such as acetylated LDL uptake. The Lin−/Flk-1+ cell population, mobilized by CO_2 bathing, was isolated and cultured with 100 nmol/L VEGF-supplemented medium for 4 days. Approximately 26±1.2% (n=12) of the Lin−/Flk-1+ cells adhered onto the fibronectin-coated plastic dishes. Approximately 74±2.3% (n=12) of the attaching cells showed the ability to incorporate the DiI-labeled acetylated LDL, and these cells expressed the VE-cadherin (Figure 7D).

Discussion

A number of reports about the physiological effects of CO_2-enriched water on subcutaneous microcirculation have been published. Savin et al[18] reported that transfer of CO_2 across the skin can have beneficial local vasomotor effects. Hartmann et al[19] demonstrated an increase in tissue oxygen brought about by the Bohr effect in addition to the vasodilation effect by CO_2 or vasodilation by decrease in plasma catecholamine levels. Toriyama et al[20] also reported that the effect of CO_2-enriched water on the subcutaneous microcirculation results from peripheral vasodilation resulting from increased parasympathetic and decreased sympathetic nerve activity. Findings in the intact coronary circulation[4] and in isolated aortic strips[5] have suggested that vasodilation in response to CO_2 may be mediated in part by NO. Consistent with these previous studies, our present study demonstrates that immersion of ischemic hindlimb into CO_2-enriched water bathing causes an NO-dependent increase in collateral blood perfusion, induction of regional VEGF synthesis, and mobilization of endothelial-lineage progenitor cells into the circulation.

What is the mechanism responsible for the proangiogenic effect by CO_2-enriched water bathing? In the endothelial cells cultured in the medium equilibrated with hypercapnia-associated acidosis, the expressions of potent angiogenic factors, such as VEGF or basic fibroblast growth factor, are increased and endothelial cell apoptosis is inhibited.[12] VEGF was well known to mobilize endothelial progenitor cells from bone marrow into the circulation.[21] Our present data clearly indicate that VEGF expression is markedly induced in hindlimb skeletal muscles after CO_2-enriched water bathing. A high concentration of CO_2 (1000 to 1200 mg/L) liberates free CO_2 in the freshwater (pH 7.0), resulting in a decrease in pH level (pH 5.0). We found that CO_2 bathing of ischemic lower limbs did not affect the pH levels in the peripheral blood and VEGF mRNA synthesis in the forelimb muscle. Considering that acidosis induces VEGF expression in the endothelial cells,[12] the local tissue acidosis by CO_2 bathing, rather than the CO_2 content of the water, may induce VEGF synthesis in the local skeletal muscles. Furthermore, calcium mobilization associated with local tissue pH changes may serve as alternate, or contributory, mechanisms for these observations.

Previous studies reported that VEGF stimulates the release of NO from the arterial wall[22,23] and promotes the recovery of disturbed endothelium-dependent flow in the ischemic hindlimb.[24] Involvement of NO in the angiogenic properties of VEGF has been established in the NO-deficient mice; Murohara et al[10] showed NO-mediated angiogenesis in the hindlimb ischemia model, and Aicher et al[25] reported that VEGF-mediated mobilization of endothelial progenitor cells is reduced in NO-deficient mice. The present study revealed that inhibition of NOS activity by L-NAME inhibited the recovery of collateral blood flow by CO_2 bathing without affecting local VEGF synthesis. Taken together, these findings demonstrate that the proangiogenic effect by CO_2 bathing is a result of activation of NO-mediated signaling and that this activation results from the downstream effects of VEGF. Considering that VEGF-mediated mobilization of endothelial

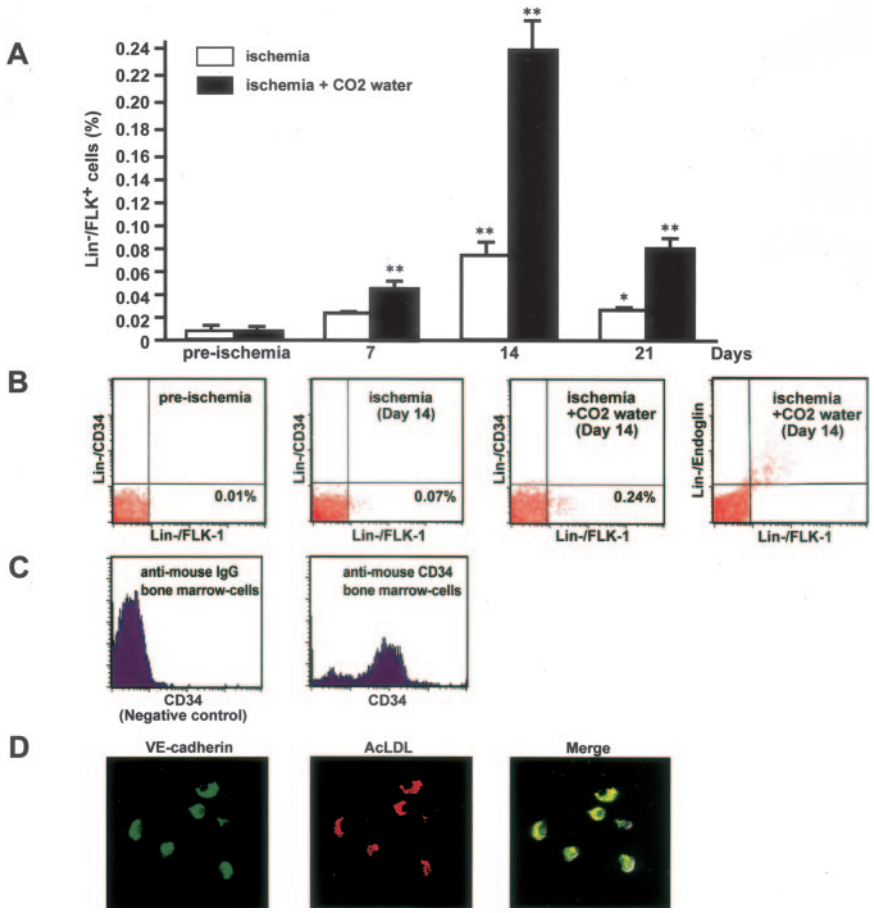

Figure 7. FACS analysis of circulating endothelial-lineage progenitor cells. A and B, Lin−/Flk+ cells in peripheral blood nuclear cells were isolated by PE-labeled lineage antigens, FITC-CD34 and biotin–Flk-1, and then analyzed. Lin−/Flk+/endoglin+ cells were isolated by FITC-labeled lineage antigens, PE-Flk-1 and biotin-endoglin. Cell number ratio of Lin−/Flk+ cells to total nuclear cells is shown (n=6 each). $^{*}P<0.05$, $^{**}P<0.001$ vs day 0 preischemic control. **C**, To prove specificity of anti-CD34 antibody, CD34+ cells in mouse bone marrow cells were enriched by biotin-labeled anti-mouse CD34 antibody and purified with streptavidin-magnet beads, followed by FACS analysis using streptavidin-PE. Rat anti-mouse IgG was used as a negative control. D, Lin−/Flk+ cells were cultured on fibronectin-coated plastic dishes in DMEM supplemented with 100 ng/mL VEGF and 10% FCS. After 4 days, DiI-labeled acetylated LDL was added into medium at 2 μg/mL for 6 hours, fixed with 4% paraformaldehyde, and stained with anti–VE-cadherin antibody and FITC-labeled anti-IgG antibody.

progenitor cells is NO-dependent,[25] our present study suggests that CO_2 bathing causes the induction of local VEGF synthesis, resulting in an NO-dependent neocapillary formation associated with mobilization of endothelial progenitor cells.

Hartman et al[19] reported that repeated CO_2-enriched water bathing increases arterial flow, transcutaneous oxygen tension, and pain-free walking distance in the clinical trial of peripheral arterial disease. Although they have not performed angiography, the enhancement of neovascularization may cause the increases in walking distance in addition to the improvement of blood vessel function. Toriyama et al[20] also showed that CO_2 foot bathing is clinically effective in the salvage of critical limb ischemia. In conclusion, our present study clearly demonstrates for the first time that CO_2-enriched water bathing causes the enhanced induction of local VEGF synthesis associated with activation of the NO-cGMP pathway and mobilization of endothelial progenitor cells, resulting in NO-dependent neocapillary formation that leads to an increase in collateral blood flow. Thus, these findings indicate that the CO_2-enriched water bathing therapy can be included in angiogenic therapies associated with neovascularization, such as the transplantation of bone marrow mononuclear cells[14] or VEGF gene therapy.[26]

Acknowledgments

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