Liposome-Encapsulated Hemoglobin Reduces the Size of Cerebral Infarction in the Rat

Evaluation With Photochemically Induced Thrombosis of the Middle Cerebral Artery

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Background and Purpose—Liposome-encapsulated hemoglobin (LEH; TRM-645) is a novel oxygen (O₂) carrier with a lower O₂ affinity (P₅₀O₂ = 40 mm Hg) than red blood cells. In contrast to cell-free hemoglobin, encapsulation prevents hemoglobin extravasation, whereas its subcellular size (230 nm) may improve O₂ delivery and limit the severity of cerebral infarction.

Methods—The extent of cerebral infarction was determined 24 hours after photochemically induced thrombosis of the middle cerebral artery from the integrated area of infarction detected by triphenyltetrazolium chloride staining in rats receiving no treatment, 10 mL/kg of LEH, homologous blood, empty liposomes, or saline. To develop a dose-response relationship, LEH dose was reduced from 10 mL/kg to 2 mL/kg, 0.4 mL/kg, and 0.08 mL/kg.

Results—Infarction extent was significantly suppressed in rats receiving LEH as compared with animals receiving no infusion, saline, empty liposome, or transfusion in the cortex but not in the basal ganglia, where all had similar degrees of damage. The dose-response relationship revealed that as little as 2 mL/kg of LEH was protective, whereas the total blood O₂ content, hemoglobin level, and transfusion and/or infusion of empty liposomes or saline were not effective.

Conclusions—Our results suggest that LEH significantly reduces the area of infarction in the cortex but not in basal ganglia after photochemically induced thrombosis of the middle cerebral artery in the rat. (Stroke. 2007;38:1626-1632.)

Key Words: cerebral infarction ■ microcirculation ■ oxygen delivery ■ reperfusion

Impairment of microcirculation after acute focal ischemia is a major factor in the pathogenesis of cerebral infarction.¹ Oxygen (O₂) delivery to areas of impending infarction is important in limiting the extent and severity of infarction, reducing neurological sequelae, and increasing patient survival. O₂ supply to such ischemic penumbrae is mainly supported by microcirculation through the capillaries, which is believed to be insufficient because of underdevelopment and a delay in recruitment.² Recent studies³,⁴ have demonstrated that plasma can perfuse and supply necessary metabolites even to the core of ischemia, but delivery of soluble O₂ is limited unless hyperbaric O₂ therapy is used.⁵ Although perfluorocarbon has been tried in acute cerebral ischemia,⁶,⁷ its efficacy remains inconsistent. Recently, cell-free hemoglobin⁸–¹⁰ has been developed as an artificial O₂ carrier; renal clearance and hypertensive response obscured neuroprotective effects in experiments⁸,⁹ and in a human trial.¹⁰ Liposome-encapsulated hemoglobin (LEH)¹¹,¹² may be effective in acute brain ischemia, because its size (230 nm) may not only prevent extravasation but also allow O₂ delivery beyond the obstruction with plasma to areas where red blood cells (RBCs) seldom reach, thereby reducing the O₂ diffusion distance. Sigmoid O₂ dissociation characteristics may allow more efficient O₂ delivery in room air than perfluorocarbon, which needs a higher O₂ inspiration because of its linear O₂ dissociation capacity.⁶,⁷ Structural similarity to RBC allows coencapsulation of an allosteric effector to modulate O₂ affinity.¹¹ The objective of this study is to evaluate the effects of LEH on photochemically induced thrombosis¹³,¹⁴ of the middle cerebral artery (MCA) in the rat.

Materials and Methods

LEH

Relevant characteristics of LEH (Terumo Co, Ltd, Tokyo, Japan) have been reported.¹¹,¹² Briefly, it is a liposome capsule measuring 230 nm in mean diameter, containing hemoglobin eluted from human RBC outdated for transfusion. The liposome capsule is coated
with polyethylene glycol to reduce aggregation and capture by the reticuloendothelial system to prolong the circulation half-life to 30 hours in rats. Inositol hexaphosphate is included for 2,3-diphosphoglycerate to adjust the O₂ affinity to P_{50O₂} conditions between 100 and 40 mm Hg. RBC is supposed to be more efficient in O₂ delivery than LEH under hypoxic conditions between 20 and 3 mm Hg.

Immediate thereafter, rats received 10 mL/kg of LEH (n=7), saline (n=6), blood (n=6), or empty liposomes (n=5) infused over 10 minutes at a slow speed (2.7 to 3.0 mL/10 minutes) to avoid acute volume load, and were compared with rats receiving no infusion (n=7). Experiments were repeated in the same way using LEH with serial 5-fold dilutions with saline so that the aliquot of infusate (10 mL/kg) would remain the same: 2 mL/kg (5-fold dilution; n=8), 0.4 mL/kg (25-fold dilution; n=8), and 0.08 mL/kg (125-fold dilution; n=6). After infusion, blood samples were taken (the “post” samples) and the infusion line was removed. Animals were placed back in cages in room air, with access to food and water ad libitum until evaluation of infarction.

Flow Patterns of RBCs and Liposomes

The flow patterns were observed through a closed cranial window under a fluorescence microscope and recorded to a high-speed video camera. The flow patterns of RBCs were observed after infusion of fluorescein-4-isothiocyanate–labeled RBCs, which emit 520 nm fluorescence in response to excitation by a mercury lamp light (wave length 490 nm). The flow patterns of liposomes were followed after infusing liposome encapsulated rhodamine-6G (0.5 mL), which emits 551 nm fluorescence in response to excitation by a halogen lamp (wave length 528 nm). These images were compared by switching fillers at the same frame from the cortical surface of the parietal lobe in rats.

Brain Damage Determination

Twenty-four hours later animals were euthanized by cervical vertebral dislocation under anesthesia after evaluating the MCA flow and obtaining a blood sample (the “1-day” sample). The brain was excised and sliced into 2-mm slices, with 2 slices anterior to and 4 slices posterior to the optical chiasm, with a brain slicer (Yuromaikii Kikai, Co, Ltd) and placed in 2,3,5-triphenyltetrazolium chloride (TTC) solution to demarcate the area of infarction. These 6 slices were placed in order, digitized, and integrated to calculate the infarcted and intact areas separately in the cortex and basal ganglia (Figure 2). After TTC staining, the brain slices were fixed with 4% formaldehyde and stained with hematoxylin-eosin, diamino-benzidine staining for iron, and immunohistochemical staining for human hemoglobin and microtubule-associated protein 2 (MAP2) by neuroanatomists (M.Y.) blind to the study protocol.

Animal Treatment

All experiments were approved by the institutional review board of Tokai University School of Medicine and Hamamatsu Photonics. Rats received humane care as required.

Statistics

The TTC-demarcated areas or the values of rats were averaged for each group and compared among groups by ANOVA with repeated measures. P<0.05 was considered significant.

Results

Flow Patterns of Liposomes and RBCs

(supplemental movie file, available online at http://stroke.ahajournals.org)

Under fluorescence microscopy (Figure 3), fluorescein-4-isothiocyanate–labeled RBCs (left panel) were identified as individual dots flowing mainly through larger vessels at either high speed (artery) or low speed (vein), whereas fluorescent liposomes (right panel) were not individually identifiable but observed as a fluid filling all vessels, in a manner similar to that of plasma, regardless of diameter or types of vessels, arteries, capillaries, or veins.

LEH Behavior, O₂ Content, and Delivery

There was no fluctuation in systemic blood pressure before and after infusion of one of the solutions of an aliquot of 10
mL/kg. Although hemoglobin levels were similar before and after onset of ischemia (Figure 4A), they became higher in transfused rats because of elimination of LEH from circulation at the time of euthanization, when MCA had been recanalized in all rats. Based on these hematocrit and LEH-crit values and their O2 binding characteristics (Figure 1), the total blood O2 content (Figure 4B) and plasma O2 content (Figure 4C, less RBC-bound O2, or sum of O2 in the plasma and LEH) were calculated for each group of rats immediately after infusion and 24 hours later. Because of simple infusion, or top load, animals receiving transfusion or LEH had higher hemoglobin levels or total blood O2 contents, regardless of the pO2 or time after administration, than rats receiving vehicle (saline or empty liposomes). Among the former, total blood O2 content (Figure 4B) was almost identical at the beginning as well as at the end of experiment, when transfused rats had a slightly higher O2 content, reflecting elimination of LEH from circulation. In contrast, plasma O2 content (Figure 4C), the sum of O2 in plasma and LEH, was calculated to be higher in LEH-treated rats than animals receiving other solutions, which had the soluble O2 alone. Although the difference appears striking (Figure 4C), the amount was less than one-tenth of the total blood O2 content because of the absence of RBC.

TTC Staining for Cerebral Infarction

Typical examples of TTC staining (Figure 2) showed that LEH treatment mainly protected the parietal and frontal cortex (white arrows) than temporal cortex (black arrows) or basal ganglia, which were consistently affected in other control animals as well. Therefore, the integrated area of damage or infarction extent (Figure 5) was significantly suppressed in rats treated with LEH (P<0.05) as compared with rats receiving no infusion, vehicles, or transfusion in the cortex but not in basal ganglia, which had a similar degree of infarction regardless of treatment. The extent of infarction appeared to correlate with plasma O2 content, but not with the total blood O2 content (transfusion versus vehicles), the presence or absence of empty liposomes or volume infusion (vehicles versus no infusion). Stepwise dilution (Figure 5) revealed that 10 mL/kg or 2 mL/kg of LEH was comparably protective, whereas 0.4 mL/kg failed to yield significant protection (P=0.07) and 0.08 mL/kg had no effect as in other control solutions.

Histopathology and LEH Staining

Morphological changes were less severe in the LEH-treated animals (LEH 10 mL/kg) in hematoxylin-eosin staining (Figure 6 upper panels) as well as in MAP2 staining (Figure 3).
6 lower panels), in which cortical architecture was preserved in the parietal lobe (Figure 2, open arrows), than in the rats receiving saline (saline 10 mL/kg), which displayed severe ischemic damage, including edema, loss of large pyramidal cells, swelling of small neurons, and spongiosis in the cortex. Immunohistochemical staining for MAP2 (Figure 7A) and human hemoglobin or iron for LEH (Figure 7B) revealed a dense expression of MAP2 with no LEH deposition in the intact hemisphere in contrast with a diffuse loss of MAP2 with intercellular LEH deposition in the ischemic hemisphere. LEH was limited to the vascular lumen in the intact tissue, detected in the intercellular space in the ischemic tissue, but not found in the vascular endothelial cells in any tissues, either intact or ischemic (Figure 7).

**Discussion**

Artificial O₂ carriers have been studied as blood substitutes mainly to reduce homologous blood transfusion.⁶⁻¹² The advantages of artificial O₂ carriers include a reduced, if not eliminated, risk of blood-borne infection and mismatch transfusion. Nonetheless, safety concerns and untoward effects still prevent clinical application, whereas short functional life may reduce their utility as blood substitutes.⁶⁻¹² Considering its perfusion characteristics deriving from its size and viscosity,¹¹,¹² we performed the current experiments to examine the hypothesis that LEH may better-perfuse collaterals and capillaries with plasma to reduce ischemic and reperfusion damage. The results suggest that LEH in a small dose (2 mL/kg) is effective in reducing the extent of infarction.
biochemically and morphologically in the cortex, but not in basal ganglia 24 hours after photochemically induced thrombosis occlusion of the MCA in a dose-dependent manner in the rat. The photochemically induced thrombosis model causes thrombotic occlusion first and reperfusion later as a result of thrombolysis,13,14 similar to the pathologic cascade occurring after clinical infarction, suggesting a use for LEH in human brain ischemia and reperfusion. Its relatively short intravascular half-life (T1/2 = 30 hours)12 may make it acceptable or even advantageous for short-term use as a therapeutic system for targeted O2 delivery to ischemic tissues, or “O2 therapeutics.”

Because ischemia impairs the active transport of electrolytes,1,16 water shifts from the intravascular compartment to the tissue, causing an increase in blood viscosity and tissue pressure,16 both of which impair microcirculation. When intracranial pressure rises as a result,17 small particles may prevent a collapse in the microcirculation.2 Nonetheless, empty liposomes failed to be protective, underscoring the importance of hemoglobin or O2-carrying capacity. Although the O2 dissociation characteristics are quite different (Figure 1), the total O2 content and average O2 delivery were mostly higher in transfused rats, which nonetheless displayed no protection, suggesting that hemoglobin or O2 transport in the form of RBCs failed to exert the protective effect. Recent studies3,4 have suggested that plasma perfuse capillaries not only to the ischemic penumbra but also to the core of ischemia even when RBC flow is severely reduced and inhomogeneous,18 providing a rationale for LEHs, but not RBCs, to perfuse, deliver O2, and thereby to be protective in brain ischemia. In this regard the effect of LEH may be similar to that of hyperbaric oxygen therapy,5 which uses plasma instead of RBCs to deliver O2. The advantages of hemoglobin-based O2 carriers such as LEH11,12 and cell-free hemoglobin8–10 over hyperbaric oxygen therapy5 or perfluorochemicals6,7 include sigmoid O2 dissociation characteristics, which allow room air respiration to be clinically efficient, as in the present study. In comparison to cell-free hemoglobins,8–10 LEH is structurally similar to RBC, encapsulated and large enough to prevent renal clearance, extravasation, or hypertension response, which might have contributed to the fact that 2 mL/kg of LEH was protective in brain ischemia.
contrast to polymerized hemoglobin, which required exchange transfusion in order to infuse 38 mL/kg, more than one-half of the total blood volume in mice (72 mL/kg). We also found LEH to be effective in much smaller doses in brain ischemia in primates (0.4 mL/kg) in wound healing (0.4 mL/kg), tumor oxygenation (5 mL/kg) and in myocardial ischemia (10 mL/kg), all known as indicators for hyperbaric O2 therapy, suggesting that effects of LEH are basically related to its O2-carrying capacity and particle size small enough to flow like plasma rather than RBC.

Artificial O2 carriers are not only delivering O2 but also acquiring O2 in the lungs as long as they remain in circulation. The amount of O2 delivered at one time by the infiltrating LEH is considered to be so small that it may not be sufficient either to save tissue, as in the basal ganglia, or to yield O2 radicals in severe hypoxia. However, multiple recirculation may make the total amount of O2 delivery significant and crucial for ischemic neurons in peril of death or apoptosis and make the reperfusion injury less severe. Such multiple recirculation with plasma may account for the cortical protection with little tissue deposition and the extended dose-response relationship; LEH was highly protective at 2 mL/kg, almost effective at 0.4 mL/kg, and not protective at 0.08 mL/kg. The absence of added protection with the use of 10 mL/kg over 2 mL/kg may suggest that 10 mL/kg is transporting more O2 than the ischemic tissue can handle and reverse protection. Benefit of LEH may not correlate with the total O2 content or delivery, but with an amount of plasma O2, much smaller than we thought, which is necessary for the ischemic neural tissue to survive before reperfusion. From the current results, however, the involvement of other functions of hemoglobin, including bicarbonate buffering, nitric oxide regulation, and leukocyte inflammatory response suppression, may not be ruled out.

Pathologic studies consistently showed less edema and ischemic damage in LEH-treated rats as compared with control animals. Immunohistochemical staining for MAP2 (A) and human hemoglobin for LEH in basal ganglia (B) in a rat treated with LEH (10 mL/kg) disclosed a diffuse loss in MAP2 reactivity with a greater accumulation of LEH in the ischemic hemisphere (right panels) than in the intact hemisphere (left panels), which showed a dense expression of MAP2 with little deposition of LEH 24 hours after the onset of ischemia. Diamino-benzidine staining for iron (B, lower panels) disclosed a dense intravascular deposition of LEH (thick arrows) in the intact tissue and vague accumulation in the ischemic tissue (thin arrows) without evidence of LEH deposition in the vascular endothelial cytoplasm (open arrows) in the intact or in the ischemic hemisphere.
indicator of acute brain injury, revealed better protection in the cortex than in basal ganglia, which in contrast had accumulated LEH. Basal ganglia were located at the core of ischemia immediately distal to photochemically induced thrombosis occlusion of MCA with little protection regardless of treatment, which in turn suggests that rats were subjected to similar degrees of ischemia. The protection by LEH was largely limited to the parietal and frontal cortex (Figure 2) located at the periphery of the ischemia, suggesting salvage by collateral circulation of LEH or developmental differences in the structure and blood supply. Overlap with LEH deposition and histological damage suggest that LEH deposition is not a mechanism of action but a consequence of ischemia, endothelial dysfunction, or breach of the blood–brain barrier. Determining the fate of the accumulated LEH in ischemic tissue will require a follow-up study to evaluate the metabolic influences and neurological consequences. Although LEH appeared to only be deposited in the ischemic neural tissue, it remained in the vascular lumen in all the other intact tissues, suggesting a slight possibility that LEH fuses with the endothelial membrane and delivers hemoglobin to its cytoplasm.

In conclusion, the results provide evidence for the beneficial effects of LEH, but not of small particles, transfusion, or total blood O2 content in reducing the extent of infarction in the cortex. A dose-response relationship revealed that as little as 2 mL/kg of LEH was effective. The actual behavior of LEH and neural tissue response may require further studies to elucidate the ischemic cerebral circulation, O2 metabolism, and reperfusion injury.

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A.T.K. and M.H. are Clinicians/Scientists at the Tokai University School of Medicine (Institute 1) and organized this study. D.F. and H.T. are Researchers employed by Hamamatsu Photonics, where all animal experiments were performed. Y.O. is a Researcher employed by Osaka Prefecture University, where all the morphological studies were performed. Because all authors had individual research funds, there is no conflict of interest.

References
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