Noninvasive Ultrasound Imaging of Inflammation Using Microbubbles Targeted to Activated Leukocytes

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Background—Lipid microbubbles used for perfusion imaging with ultrasound are retained within inflamed tissue because of complement-mediated attachment to leukocytes within venules. We hypothesized that incorporation of phosphatidylserine (PS) into the microbubble shell may enhance these interactions by amplifying complement activation and thereby allow ultrasound imaging of inflammation.

Methods and Results—In 6 mice, intravital microscopy of tissue necrosis factor-α–treated cremaster muscle was performed to assess the microvascular behavior of fluorescein-labeled lipid microbubbles with and without PS in the shell. Ten minutes after intravenous injection, microbubble attachment to leukocytes within inflamed venules was greater for PS-containing than for standard lipid microbubbles (20 ± 4 versus 10 ± 3 per 20 optical fields, P < 0.05). The ultrasound signal from retained microbubbles was assessed in the kidneys of 6 mice undergoing renal ischemia-reperfusion injury and in 6 control kidneys. The signal from retained microbubbles in control kidneys was low (<2.5 video intensity units) for both agents. After ischemia-reperfusion, the signal from retained microbubbles was 2-fold higher for PS-containing than for standard lipid microbubbles (18 ± 6 versus 8 ± 2 video intensity units, P < 0.05). An excellent relation was found between the ultrasound signal from retained microbubbles and the degree of renal inflammation, assessed by tissue myeloperoxidase activity.

Conclusions—We conclude that noninvasive assessment of inflammation is possible by ultrasound imaging of microbubbles targeted to activated leukocytes by the presence of PS in the lipid shell. (Circulation. 2000;102:2745-2750.)

Key Words: echocardiography • inflammation • leukocytes

Inflammation is a common pathophysiological process in innumerable disease states. A noninvasive imaging method capable of routinely assessing inflammation in vivo would be invaluable as a diagnostic test and for assessing response to therapy.

Gas-filled, encapsulated microbubbles are currently used to assess tissue microvascular perfusion during ultrasound imaging. To satisfy the requirements of a flow tracer, these microbubbles have been designed to possess rheological properties similar to those of red blood cells and normally transit through the microcirculation unimpeded.1,2 We have recently shown, however, that microbubbles with shells composed of albumin or lipid can bind to activated neutrophils and monocytes3 and are thereby retained within the microcirculation of inflamed or injured tissues.4 Within minutes of binding, most microbubbles are phagocytosed, yet they remain acoustically active, so their ultrasound signal in inflamed tissue may be detected after clearance of circulating microbubbles from the blood pool.3

The signal intensity from microbubbles retained in regions of inflammation is low because of the relatively small proportion of microbubbles that interact with leukocytes within venules3,5 and of viscoelastic damping of microbubbles once they are phagocytosed.3 Amplification of this signal may be possible if microbubble avidity for activated leukocytes could be increased. Attachment of lipid microbubbles to activated leukocytes is mediated largely by serum complement.4 Opsonization may potentially be enhanced by incorporation of certain moieties in the lipid microbubble shell that amplify complement activation. Prior studies investigating the influence of lipid content on liposome behavior have demonstrated that incorporation of phosphatidylserine (PS) into the membrane accelerates complement activation6–8 and promotes liposome attachment to monocyte-derived cells.8–10

In the present study, we hypothesized that the presence of PS in the lipid shells of microbubbles would enhance their microvascular retention in inflamed tissue. Intravital micros-
copy was used to quantify the extent of interactions between leukocytes and lipid microbubbles with and without PS in their shells. The potential application of PS-containing microbubbles for the assessment of inflammation using noninvasive ultrasound imaging was tested in mice undergoing ischemia-reperfusion of the kidney.

Methods

Microbubbles
Microbubbles with lipid shells (MP1950, Mallinkrodt Inc) were prepared by sonication of decafluorobutane gas with aqueous dispersion of 1 mg/mL poly(ethylene glycol) stearate (Sigma Chemical Co) and 2 mg/mL distearoyl phosphatidylcholine (Avanti Polar Lipids) in normal saline. Microbubbles containing PS (MP1950-PS, Mallinkrodt Inc) were prepared by addition of 0.3 mg/mL distearoyl-PS (Avanti Polar Lipids) to the dispersion. The mean diameters for MP1950 and MP1950-PS were similar (3.2±0.4 versus 3.2±0.6 μm, P=0.86).

Flow Cytometry
Binding of FITC–labeled annexin V to the microbubble shell was used to confirm the presence of PS.11 MP1950 and MP1950-PS microbubbles (2×10⁷) were placed in 200 μL of 10 mmol/L HEPES, 140 mmol/L NaCl, and 2.5 mmol/L CaCl₂ (pH 7.4). Half of the microbubble suspension was used as a control, and the other half was incubated with FITC–annexin V conjugate (Molecular Probes, Inc) for 15 minutes. Microbubbles were washed and analyzed in triplicate (1×10⁸ events for each) on a FACSCalibur (Becton Dickinson). Data were displayed as histograms of green fluorescence intensity. Positive staining for FITC-conjugated annexin V was defined as appearance of microbubbles within a fluorescence intensity gate that excluded 99% of the control microbubbles.

Animal Preparation
The study protocol was approved by the animal research committee at the University of Virginia. Fifteen wild-type C57BL/6 mice (24 to 30 g) were anesthetized with an intraperitoneal injection (12.5 μL/g) of a solution containing ketamine hydrochloride (10 mg/mL), xylazine (1 mg/mL), and atropine (0.02 mg/mL). Body temperature was maintained at 37°C with a heating pad. Anesthesia was maintained with intravenous administration of 0.1 mg pentobarbital approximately every 45 minutes as needed.

Intravital Microscopy
In 6 mice, cremaster muscle inflammation was produced by intracrotal injections of 0.5 μg murine TNF-α (Genzyme Corp) in 0.2 mL saline. Two hours later, the animal was anesthetized, and the jugular veins were cannulated for administration of microbubbles and drugs. The right or left cremaster muscle was exteriorized through a scrotal incision and prepared for intravital microscopy. A longitudinal incision was made in the muscle, and the edges were secured to a translucent pedestal. The preparation was superfused continuously with isothermic bicarbonate-buffered saline. Microscopic observations were made with an Axioskop2-FS microscope (Carl Zeiss, Inc) with an saline-immersion objective (SW 40/0.8 numerical aperture). Fluorescent epi-illumination was performed with a 460- to 500-nm excitation filter. Video recordings were made with a high-resolution CCD camera (C2400, Hamamatsu Photonics) connected to an S-VHS recorder (S9500, JVC).

Microbubbles were fluorescently labeled by addition of a fluorescent lipid probe with a peak excitation wavelength of 484 nm (Molecular Probes) before sonication. Intravenous injections of 1×10⁷ fluorescent MP1950 or MP1950-PS microbubbles were made in random order separated by 20-minute intervals. Two and 10 minutes after each injection, 20 optical fields encompassing a single venular system with diameters of 25 to 40 μm were observed under fluorescent epi-illumination to determine the number of retained microbubbles. The same venular segments were observed for each injection.

Renal Ischemia and Reperfusion
In 6 mice, either the right or left kidney was exposed with a dorsal midline skin incision and paramedian opening of the retroperitoneal space. A hemostatic microvascular clamp (B-1A, ASSI Corp) was placed on the renal pedicle for 30 minutes. Cessation of renal blood flow and subsequent reperfusion were confirmed by tissue pallor during arterial occlusion and prompt return of tissue color after reflow.15 The surgical wound was closed in layers, and subcutaneous buprenorphine (0.2 μg/g) was given for analgesia.

Renal Ultrasound
Renal ultrasound was performed in the 6 mice undergoing renal ischemia 2 hours after reflow. Bilateral renal ultrasound was also performed in 3 control mice that did not undergo surgery. Animals were anesthetized, and a catheter was placed in a jugular vein for microbubble administration. Imaging was performed at 3.3 MHz with a linear-array transducer interfaced with an ultrasound system (HDi-5000, ATL Ultrasound). Pulse-inversion imaging was used, which improves microbubble signal-to-noise ratio by transmitting 2 sequential pulses of ultrasound that are phase-inverted by 180° so that summation of the 2 sets of radiofrequency responses results in cancellation of tissue signal but not the nonlinear signals produced by microbubbles.16 Images were acquired in a paraspinol long-axis view with the transducer fixed in position with a free-standing clamp. A mechanical index of 0.8 was used, and the acoustic focus was placed at the level of the renal pelvis. Gain settings were optimized and held constant. Data were recorded on 1.25-cm videotape with an S-VHS recorder (Panasonic MD830, Matsushita Electric).

Before microbubble injection, baseline images were acquired at a pulsing interval (PI) of 1 second. Ultrasound transmission was then suspended, and 1×10⁷ MP1950 or MP1950-PS microbubbles were injected as an intravenous bolus. The basis for the imaging protocol used to detect retained microbubbles is schematically depicted in Figure 1. Immediately after injection, a very high concentration of freely circulating microbubbles in the blood pool is expected (1A). Ultrasound imaging was therefore not resumed until 12 minutes after each injection, when the blood pool concentration of freely circulating microbubbles should be low. The video intensity (VI) in the initial frame on resumption of imaging 12 minutes after injection (1B) should therefore reflect the total tissue concentration of microbubbles (both retained and freely circulating).14 The VI on the next...
few frames (1C) should be lower as a result of destruction of microbubbles by the first and subsequent pulses. After acquisition of several frames, the PI was increased to 20 seconds to allow time for complete replenishment of the beam with microbubbles to assess the signal from any freely circulating microbubbles still present (1D). Images were analyzed off-line as previously described. Several precontrast frames were averaged and digitally subtracted from the initial frame obtained on resumption of imaging 12 minutes after microbubble administration and from averaged frames obtained at PIs of 1 and 20 seconds. Background-subtracted VI was measured from a region of interest placed around the entire kidney.

**Tissue Myeloperoxidase Activity**

Renal myeloperoxidase activity was measured to assess tissue neutrophil accumulation. Tissue was homogenized in ice-cold 20 mmol/L potassium phosphate buffer (pH 7.4) and centrifuged at 17 000 g for 20 minutes at 4°C. The pellet was resuspended in 0.5% hexadecyl-trimethylammonium bromide/10 mmol/L EDTA in 50 mmol/L potassium phosphate buffer (pH 7.4) and centrifuged at 20 000 g for 3 minutes, and incubated for 20 minutes at 4°C. After centrifugation, the supernatant was removed and diluted 1:4 in assay buffer. Changes in absorbance were recorded at 460 nm over 5 minutes with a microplate reader (Multiskan MS, Labsystems Inc) and were analyzed with software (Genesis-Lite, Labsystems Inc) resident on a computer workstation. One unit of activity was defined as change in absorbance of 1.0/min at 25°C. Results were given as units of myeloperoxidase activity per gram of protein, determined by BCA assay (Pierce Chemical Co).

**Immunohistochemistry**

Immunostaining for neutrophils was performed on paraffin-embedded sections of renal tissue. A primary rat anti-mouse antibody (7/4, Serotec Inc) against a polymorphic 40-kDa antigen expressed by neutrophils was placed on the slides overnight at 4°C. The slides were washed, and a biotinylated rabbit anti-rat secondary antibody (Vector Laboratories) was placed on the slides for 1 hour. Staining was performed with a peroxidase kit (ABC Vectastain Elite, Vector Laboratories) and 3,3’-diaminobenzidine chromagen (DAKO). Slides were counterstained with hematoxylin.

**Statistical Methods**

Data are expressed as mean±SD. Interval comparisons were made with repeated-measures ANOVA. Correlations were made by multiple regression analysis. Differences were considered significant at a value of P<0.05 (2-sided).

**Results**

**Flow Cytometry**

The histograms of green fluorescence intensity obtained by flow cytometry (Figure 2) illustrate binding of FITC-conjugated annexin V to MP1950-PS microbubbles. Fluorescence intensity was low for the control suspension of MP1950-PS and increased when MP1950-PS was incubated with FITC-conjugated annexin V, confirming the presence of PS in the shell. Compared with MP1950, MP1950-PS was characterized by a higher percentage of microbubbles staining positive for FITC-conjugated annexin V (53±3% versus 16±9%, P<0.05) and a greater mean fluorescence intensity (15±4 versus 7±3, P<0.05).

**Microbubble Retention in Inflamed Venules**

The mean blood flow velocity and shear rate in the study venules of the mouse cremaster muscle were 203±703 μm/s and 987±302 s⁻¹, respectively. The degree of leukocyte adhesion after TNF-α was high (1061±305/mm²), indicating a pronounced inflammatory response. Leukocyte adhesion was not altered by injection of MP1950-PS (1074±291 versus 1037±351/mm² for preinjection and postinjection, P=0.81).

Microbubble injections were well tolerated in all mice and caused no changes in vessel hemodynamics. On fluorescent epi-illumination, the number of microbubbles retained within inflamed venules 2 minutes after their injection was 2-fold greater for MP1950-PS than for MP1950 (Figure 3). The number of microbubbles retained was even greater at 10 minutes because of their accumulation but remained 2-fold greater for MP1950-PS (Figure 3). Microbubble retention was entirely due to their attachment and eventual phagocytosis by activated leukocytes adherent to the venular endothelium (Figure 4). Freely circulating microbubbles were infrequently observed at the 10-minute interval (<1 microbubble transiting every 5 seconds).

**Figure 3.** Mean (±SEM) number of MP1950 and MP1950-PS microbubbles retained within cremaster venules 2 and 10 minutes after intravenous injections of microbubbles. OF indicates optical fields. *P<0.01 vs MP1950; †P<0.05 vs 2-minute measurement.

**Figure 4.** Examples of images obtained by intravital microscopy 2 minutes after injection of MP1950-PS microbubbles. Leukocyte adhesion to venular wall, seen during transillumination, reflects an inflammatory response. Fluorescent epi-illumination revealed a microbubble attached to adhered leukocyte, denoted by arrow in transillumination image.
Assessment of Renal Inflammation

Renal myeloperoxidase activity after 30 minutes of warm ischemia and 2 hours of reperfusion was high compared with control kidneys (7.5 ± 3.0 vs 0.5 ± 0.3 U, P < 0.01). Immunohistology revealed neutrophil infiltration in the glomeruli and in the peritubular regions of the outer medulla and cortex after ischemia-reperfusion (Figure 5B and 5C). Neutrophil infiltration was most abundant at the corticomedullary junction, where intraluminal debris and occasional sloughing of tubular cells were also seen (Figure 5D). These findings were not present in control kidneys (Figure 5A).

The Table shows the background-subtracted VI data obtained by renal ultrasound 12 minutes after microbubble injection. The VI in the initial frame (reflecting both retained and freely circulating microbubbles) in kidneys undergoing ischemia-reperfusion was significantly higher than in control kidneys (P < 0.001) for both microbubble agents; however, this difference was greater for MP1950-PS than for MP1950 microbubbles (P < 0.01). In all groups, VI on subsequent frames obtained at a PI of 1 second was very low, indicating destruction of all microbubbles by the first few ultrasound frames. The VI increased minimally when the PI was increased to 20 seconds, indicating the presence of very few freely circulating microbubbles. Examples of background-subtracted color-coded renal ultrasound images are shown in Figure 6. On the initial frame obtained 12 minutes after contrast injection, there is intense opacification of the postischemic but not the control kidney. The signal in averaged frames obtained subsequently at a PI of 1 second was very low, indicating destruction of retained microbubbles. This signal remained low at a PI of 20 seconds, indicating a low concentration of freely circulating microbubbles.

The acoustic signal from retained microbubbles alone was calculated by subtracting the VI at a PI of 20 seconds (reflecting freely circulating microbubbles) from that on the initial frame (reflecting retained and freely circulating microbubbles). The mean acoustic signals from retained microbubbles are depicted in Figure 7 according to the degree of inflammation by renal myeloperoxidase activity. In control kidneys, the myeloperoxidase activity and the signal from retained microbubbles was low. Compared with control kidneys, ischemia-reperfusion–injured kidneys were characterized by much higher (P < 0.001) myeloperoxidase activity and signal intensity from retained microbubbles. In these kidneys, the mean signal from MP1950-PS was >2-fold higher than MP1950 (P < 0.01). The correlation between myeloperoxidase activity and the acoustic signal from retained microbubbles in kidneys was linear for MP1950 (r = 0.67, SEE = 6.9, P < 0.05) and MP1950 (r = 0.69, SEE = 2.7, P < 0.05) microbubbles. The signal intensity from retained MP1950 microbubbles was not influenced by the order of microbubble injection.

Discussion

We have previously shown that lipid microbubbles are retained within the microcirculation of inflamed tissue because of their attachment to leukocytes adherent to the venular wall. In this study, we have demonstrated that interactions between leukocytes and lipid microbubbles in vivo can be enhanced by altering the shell composition. The presence of PS in the microbubble shell resulted in greater accumulation of microbubbles within inflamed tissue, thereby allowing an accurate assessment of inflammation during ultrasound imaging. This study is the first to demonstrate that contrast ultrasound with intravenous administration of microbubbles can be used to assess inflammation in an organ system.

The molecular mediators of inflammation and toxic products of infiltrating leukocytes have been implicated in tissue damage and organ dysfunction in innumerable disease states. Recently, noninvasive imaging techniques such as computed tomography, magnetic resonance, and ultrasound have been used to detect anatomic alterations associated with inflammation (such as edema). This information is limited, however, by the lack of specificity and inability to discriminate acute from chronic changes. Radionuclide imaging has also been used to evaluate issue inflammation by use of 111In- or 99mTc-labeled leukocytes, which accumulate in inflamed tis-
sue, and gallium-67 citrate, which extravasates and is retained in regions of increased capillary permeability. Widespread application of these techniques has been limited by the complicated and time-consuming protocols, expense, high radiation burden, and nonspecific tracer uptake in different circumstances is due primarily to enhanced activation of serum complement by either the classic or alternative pathway. In our present study, intravital microscopy revealed a 2-fold increase of microbubble retention within inflamed tissue by incorporating PS into the microbubble shell.

Whether increased retention of PS-containing microbubbles significantly influenced the ultrasound signal in inflamed tissue imaged in vivo was investigated in a model of renal ischemia-reperfusion injury in mice. Renal inflammation after 30 minutes of warm ischemia and 2 hours of reperfusion was confirmed on immunohistology by neutrophil infiltration in the cortex and especially in the outer rim of the medulla, where expression of proinflammatory cytokines is highest after ischemia-reperfusion. The degree of inflammation was quantified by myeloperoxidase activity, which was markedly elevated after ischemia-reperfusion injury compared to control kidneys. In postischemic kidneys, the ultrasound signal from retained MP1950-PS microbubbles was 2-fold greater than that found with MP1950. A linear relation was found between the extent of inflammation by myeloperoxidase activity and by ultrasound signal from retained MP1950-PS microbubbles.

Although our studies confirm that the presence of PS in the shell of microbubbles enhances their retention in inflamed tissue, we did not necessarily demonstrate that this effect was due entirely to amplification of complement activation. Complement-independent mechanisms for stimulated uptake of PS-containing particles or cells has recently been demonstrated. These mechanisms include direct interactions with scavenger receptors, thrombospondin-mediated binding to αvβ3-integrins, or binding of autologous proteins such as β2-glycoprotein 1 that facilitate phagocytosis. We also did not directly assess any time-dependent influence of MP1950-PS on the inflammatory response. There were no effects, however, of MP1950-PS on the mean number of leukocytes or the extent of MP1950 attachment to leukocytes, implying little potentiation of the inflammatory response.

Retention of microbubbles as a marker of injury in humans has so far been demonstrated only with direct arterial injections of microbubbles into the myocardium immediately after cardioplegic arrest. Our present results are encouraging that intravenously administered microbubbles may be used for this purpose. In this study, optimization of the signal-to-noise
ratio for phagocytosed microbubbles was necessary. This was done with a novel imaging method that greatly suppresses tissue signal16 and by acquisition of images late after microbubble injection, which allowed clearance of almost all freely circulating microbubbles from the blood pool, confirmed by intravital microscopy and VI measurements at a long PI.

This study indicates that ultrasound detection of microbubbles retained by activated leukocytes may provide a method for noninvasively assessing the spatial distribution and severity of inflammation. By changing the lipid composition of the microbubble shell, we have increased the avidity of lipid microbubbles for activated leukocytes and thereby enhanced the signal generated during ultrasound imaging of inflamed tissues. The clinical importance of these observations is underscored by the consideration that compared with the radionuclide imaging techniques discussed earlier, ultrasound examination is inexpensive, can be performed rapidly and at the bedside, is widely available, and has a better spatial resolution. Furthermore, the ability to target microbubbles to activated leukocytes in inflamed tissue may also be important for the potential application of microbubbles as vehicles for drug or gene delivery to regions of inflammation.

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