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of LV at risk was calculated as the ratio of the LV volume excluding Evans blue dye to the total LV volume. Infarct size was calculated as the ratio of the infarct volume to the volume of the risk area as previously described.[26] Animals with infarct volume in the 35 to 70% range of total LV volume were used as inclusion criteria in the study.[27] Only one mouse was excluded based on these criteria.

Lactate Dehydrogenase (LDH) and Creatine Kinase (CK) Activity in Plasma

Biochemical analysis of myocardial injury was performed in heparinized arterial blood collected at termination of the experiment. Plasma LDH and CK were measured using an automated clinical analyzer at the Clinical Analysis at the Kingston General Hospital using clinical grade reagents.

Vascular Permeability Assay in Cardiac Tissue

Forty-eight hours after reperfusion, mice (8 to 12 weeks) were anesthetized by an intraperitoneal injection of pentobarbital (45 mg/kg). ^{125}I-albumin (10^6 cpm/1.44 mCi/mg; MP Biomedicals, Inc., Mississauga, Canada) was injected into the right external jugular vein via a PE-50 catheter. Twenty minutes after injection, the mice were euthanized, and blood was obtained as above and weighed. Exsanguination and removal of excess ^{125}I-albumin proceeded via the right atrium. A 23-gauge needle was inserted into the apex of the left ventricle and the mouse was perfused retrogradely at 40 mmHg with 5.85 ml/100 g of 0.9% NaCl containing 100 U/ml heparin as described previously.[28] The LAD was then religated and Evans blue dye was perfused as above to delineate the risk area, which was then dissected from the remaining myocardial tissue, weighed, and placed in individual tubes. The radioactivity in the blood, nonrisk area, and risk area were counted separately using a gamma counter (Beckman Instruments, Irvine, CA). The permeability index of the different regions was calculated as the radioactivity per g of wet tissue divided by the radioactivity in 1 g of blood.[29] Sham-surgery controls were subjected to the same manipulations, with the exception that the ligature was not tied.

RNA Extraction and Real-Time Polymerase Chain Reaction (PCR)

Total RNA was isolated from the risk area of the left ventricle 3 hours after reperfusion using Trizol reagent (Sigma). Total RNA was reverse-transcribed to cDNA using the Synthesis System for RT-PCR kit (Invitrogen, Carlsbad, CA) according to the manufacturer's protocol. For detection of mouse gene expression, quantitative real-time PCR was performed using a 7500 thermal cycler with TaqMan Universal PCR master mix and TaqMan gene expression assays (Egr-1, VCAM-1, and ICAM-1; Applied Biosystems, Foster City, CA) or with SYBR Green PCR master mix ($CysLT_1R$, and $CysLT_2R$) as described.[16] GAPDH was used as a control housekeeping gene. Data are calculated by the $2^{-}\Delta\Delta CT$ method and are presented as fold induction of transcripts for target genes normalized to GAPDH, with respect to the sham controls.[30]

Terminal Deoxynucleotidyl Transferase-Mediated dUTP Nick End-Labeling (TUNEL) Staining

TUNEL assays were performed on LV samples with the CardioTACS *in situ* apoptosis detection kit (Trevigen, Gaithersburg, MD) as described by Takahashi and colleagues[31] with some modification. The hearts were arrested in diastole with 0.2 N KCl 48 hours after reperfusion and perfused with 3.7% neutralized formaldehyde solution. The heart was then excised, postfixed in the same fixative for another 12 hours, then cut into three sections corresponding approximately to the apex, mid-papillary, and base. The slices were embedded in paraffin, cut into 5-μm sections, and transferred to silicon-coated slides. High-power fields (12 to 20 at X400 magnification) were obtained at the different levels to measure the number of TUNEL-positive cardiomyocyte nuclei in the peri-infarct border and uninfarcted remote zones, respectively. Only nuclei that were clearly located in cardiomyocytes were scored. The number of TUNEL-positive cardiomyocyte nuclei was divided by the total number of nuclei to determine the ratio of TUNEL-positive nuclei.

Immunohistochemical Staining

To determine the numbers of infiltrating leukocytes, formalin-fixed, paraffin-embedded 4-μm sections were mounted on silicon-coated slides and treated with 3% H_2O_2 to block endogenous peroxidase. The sections were incubated for 1 hour at room temperature with rat polyclonal anti-mouse CD45 antibody (PharMingen, San Diego, CA) at a dilution of 1:50. The sections were then incubated with biotinylated rabbit IgG (Vector Laboratories, Burlingame, CA), and CD45 immunoreactivity was visualized using diaminobenzidine substrate. The number of leukocytes in the boundary area was counted in 10 random high-power fields, and the average number in each group was calculated.[32] X-gal staining to determine endogenous $CysLT_2R$ expression based on the LacZ reporter gene was performed essentially as described.[33] AQ: C

Echocardiography

Mice (8 to 12 weeks) underwent transthoracic echocardiography 1 day before and 2 weeks after acute I/R using a HP (Phillips) Sonos 5500 equipped with a 15-6L (15-6 MHz) intraoperative linear array transducer essentially as previously described.[34] The 2-week time point was chosen as one of the earliest time points to clearly define remodeling responses in rodents.[34] Briefly, in preparation for echocardiography, animals were lightly anesthe- AQ: D

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tized by halothane using a nose cone, shaved, and positioned on a heated pad in a recumbent position. Measurements were performed at the midpapillary level from well aligned M-mode images from the parasternal short-axis view. LVd (LV diastolic diameter), PWd (end-diastolic posterior wall thickness), and IVSd (interventricular septum thickness) were determined. The relative wall thickness for each level of the LV was calculated as (PWd + IVSd)/LVd. For each parameter, an average of five cardiac cycles was used for calculations.

Hemodynamic Measurements

Two weeks after acute I/R injury, mice were anesthetized with isoflurane (2%) in medical grade oxygen. The animals were then intubated and ventilated using a pressure controlled respirator (Kent Scientific Corp., Litchfield, CN) at a tidal volume of 200 μl and a frequency of 130 strokes/minute. Body temperature was monitored with a rectal thermometer and maintained at 37°C with the aid of a heat lamp. A midsternal thoracotomy was performed as above to expose the heart. The right jugular vein was cannulated for drug administration. A 1.4F ultra-miniature Millar catheter (SPR 839, Millar Instruments, Houston, TX) was placed into the left ventricle through the apex to record LV pressure. After recording steady-state LV pressures, mice were given an intravenous administration of the synthetic catecholamine dobutamine (40 ng/g body weight) to investigate the functional integrity of adrenergic signaling in the heart. The peak hemodynamic response was recorded using a data acquisition system (PVAN, Millar Instruments). The PVAN software was used for off-line calculation of LV peak systolic pressure, LV end-diastolic pressure, LV peak-positive developed pressure (dP/dt_{max}), LV peak-negative developed pressure (dP/dt_{min}), LV pressure at peak positive developed pressure ($P@dP/dt_{max}$), heart rate, and tau (τ) as described.[35] For calculation of hemodynamic parameters, a minimum of 50 consecutive cardiac cycles were used.

Statistical Analysis

All data are expressed as mean ± SEM. One-way analysis of variance followed by Student-Neuman-Keuls *t*-test were used to compare differences in risk area, infarct size, myocardial enzyme activities, and endothelial permeability, as well as differences in inflammatory gene expression and cardiomyocyte apoptosis. Unpaired *t*-test was used to compare differences in neutrophil infiltration and echocardiographic and functional parameters between tg and ntg mice. Paired *t*-test was used to compare before and after I/R changes in echocardiographic parameters and LV functional responses to dobutamine in the same animals. A P value <0.05 was considered to indicate statistical significance.

Results

CysLT Receptor Expression in Mouse Hearts

The expression of both native murine $CysLT_1R$ and $CysLT_2R$ was examined in hearts by real-time quantitative PCR as previously done in mouse ear tissue.[16] Gene expression of both CysLT receptors was low in noninfarcted ntg hearts and in infarcted hearts 3 hours after I/R injury (Figure 1). However, 48 hours after I/R injury F1
$CysLT_1R$ expression had increased 7.5-fold whereas $CysLT_2R$ expression increased 3.5-fold. The human $CysLT_2R$ transgene, using specific primers that can distinguish between species, could only be detected in tg mice. Using a second independent technique, we were also able to document elevation of $CysLT_2R$ expression after 48 hours of I/R. Thus, using a novel mouse strain in which the *Cysltr2* gene is deleted and replaced with a LacZ reporter gene under control of the *Cysltr2* gene regulatory elements (S. Ishii et al, unpublished data) we were able to demonstrate sparse blue X-gal staining in noninfarcted ventricular tissue and 3 hours after I/R injury (Figure 1, B and C), consistent with the pattern observed previously by *in situ*

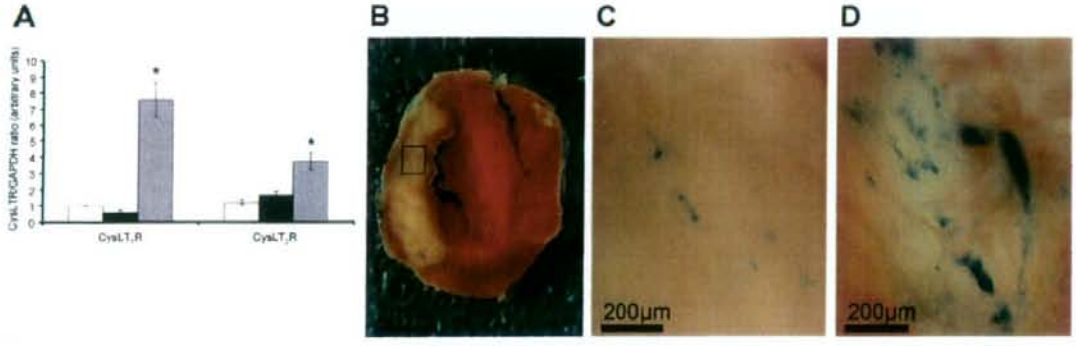

Figure 1. Expression of $CysLT_1R$ and $CysLT_2R$ in mouse hearts. **A:** Quantitative real-time PCR was used to assess gene expression for the two CysLT receptors relative to GAPDH expression in ntg mouse hearts ($n = 3$) as described in the Materials and Methods section. **Open bars**, sham-operated mice; **black bars**, hearts 3 hours after I/R; **cross-hatched bars**, hearts 48 hours after I/R. $^*P < 0.05$ compared to sham-operated controls. **B:** TTC-stained heart slice from a $CysLT_2R$-deficient LacZ mouse 3 hours after I/R injury. **C:** Representative $CysLT_2R$ expression in **boxed region** of the slice shown in **B** detected via the reporter gene LacZ with blue X-gal staining. **D:** $CysLT_2R$ expression (via reporter LacZ/X-gal staining) in a heart slice from a $CysLT_2R$-deficient LacZ mouse having undergone 48 hours of I/R. Similar patterns of expression were observed in two additional mice at 3 and 48 hours after I/R.

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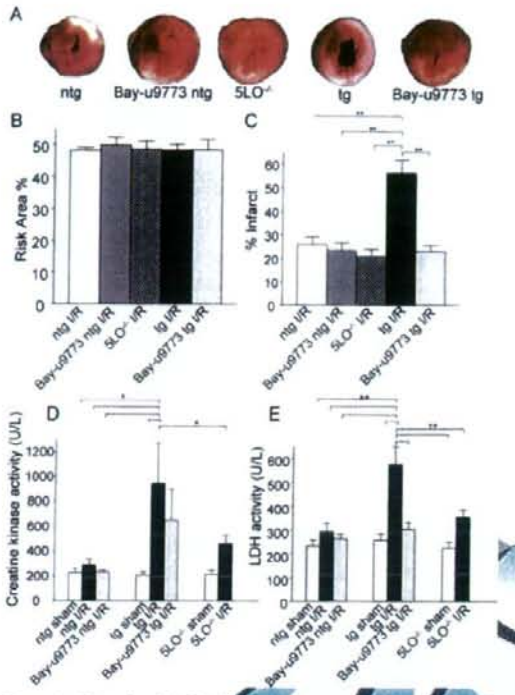

Figure 2. Effect of endothelial $CysLT_2R$ overexpression on LV infarct size after acute I/R injury. **A:** Representative TTC-stained transmural sections from ntg, tg, and $5LO^{-/-}$ mice at 48 hours after I/R. Representative sections of ntg and tg mice treated with the nonselective dual $CysLT_1R/CysLT_2R$ receptor antagonist Bay-u9773 are also shown. **B:** Morphometric analysis of LV area at risk (**B**) and infarct size (**C**) in the five groups mentioned above. **D** and **E:** Serum levels of CK (**D**) and LDH (**E**) in sham and infarcted ntg, tg, and $5LO^{-/-}$ mice at 48 hours after reperfusion. $^*P < 0.05$; $^{**}P < 0.01$; $n = 8$ for groups in **A–C**; $n = 6$ for groups in **D** and **E**.

hybridization in normal mouse heart.[15] After 48 hours of I/R injury, staining intensity increased in the infarct and peri-infarct zones (Figure 1D), which was in harmony with the PCR data.

Endothelial $CysLT_2R$ Overexpression Increases Myocardial Infarct Size after LAD Occlusion and Reperfusion

The effect of endothelial overexpression of $CysLT_2R$ on myocardial I/R injury is shown in Figure 2. Gross histological analysis of TTC-stained sections 48 hours after reperfusion showed a larger necrotic area in tg animals compared to ntg littermates and 5-lipoxygenase-null $5LO^{-/-}$ mice (Figure 2A). Histomorphometric analysis revealed that infarct size in $CysLT_2R$ tg mice was increased by 114% relative to ntg mice (56 ± 15% versus 26 ± 9%, $n = 8$, $P < 0.01$) (Figure 2C), despite comparable risk area in all groups (Figure 1B). Infarct size in the $5LO^{-/-}$ null mice was comparable to ntg mice (21 ± 9% versus 26 ± 9%). Treatment of tg mice with the nonselective dual $CysLT_1R/CysLT_2R$ antagonist Bay-u9773, at a dose tested empirically to evoke $CysLT_2R$ antagonism, markedly reduced infarct size by nearly 60% (56% versus 23%, $n = 8$, $P < 0.05$) to levels comparable to ntg and $5LO^{-/-}$ mice (Figure 2, A and C). The antagonist had no additional effect on infarct size in ntg mice.

We measured serum levels of CK and LDH 48 hours after reperfusion. CK (Figure 2D) and LDH (Figure 2E) activities in infarcted ntg mice were increased by ~26% compared to the baseline levels in sham-operated controls. In contrast, CK and LDH levels were markedly elevated by 357% and 123%, respectively, in tg mice subjected to I/R compared to tg sham controls (Figure 2, D and E). Compared to ntg I/R mice, the levels of CK and LDH were elevated by ~230% and 100%, respectively, in tg mice. In concordance with the histopathological findings, treatment with Bay-u9773 reduced levels of CK and LDH after reperfusion in the tg animals (Figure 2, D and E), while having no significant effect on these markers in ntg mice. I/R increased the levels of CK and LDH in $5LO^{-/-}$ mice but this was significantly smaller than in tg mice (Figure 2, D and E).

Endothelial $CysLT_2R$ Overexpression Increases Permeability in the Infarcted Region of Transgenic Mouse Hearts

Previously we detected enhanced vascular permeability responses to leukotriene challenge and passive cutaneous anaphylaxis in mouse ear vasculature of tg mice.[16] To examine if similar vascular responses occur in the coronary endothelium after myocardial I/R, we assessed the histopathology of the infarct. In addition, we measured extravasation of ^{125}I-BSA in the ischemic and remote areas of the left ventricle at 48 hours after reperfusion. Microscopic examination of the infarct in hematoxylin and eosin (H&E)-stained sections showed minimal accumulation of erythrocytes in the infarcted region of ntg mice (Figure 3A). In contrast, tg mice presented significant accumulation of red cells in the interstitium, resulting in hemorrhage of the infarcted area (Figure 3B). Basal coronary endothelial permeability to ^{125}I-BSA did not differ significantly between ntg and tg mice (Figure 3C). I/R injury led to significant interstitial accumulation of ^{125}I-BSA in both ntg and tg mice. However, the increase in coronary circulation permeability was more pronounced in tg versus ntg mice (202% versus 93%, Figure 3C). No differences in permeability were seen in the nonischemic region of the myocardium.

Endothelial $CysLT_2R$ Overexpression Increases $CD45^+$ Leukocyte Infiltration after I/R in Transgenic Mouse Hearts

We used immunostaining of the pan leukocyte cell surface marker CD45 to determine whether the enhanced permeability of coronary endothelium leads to increased leukocyte infiltration of the infarcted region after I/R injury. Figure 4A shows representative cross-sections from the peri-infarct region in ntg and tg mice. The tg mice showed greater density of CD45-positive cells than ntg mice. Morphometric analysis showed

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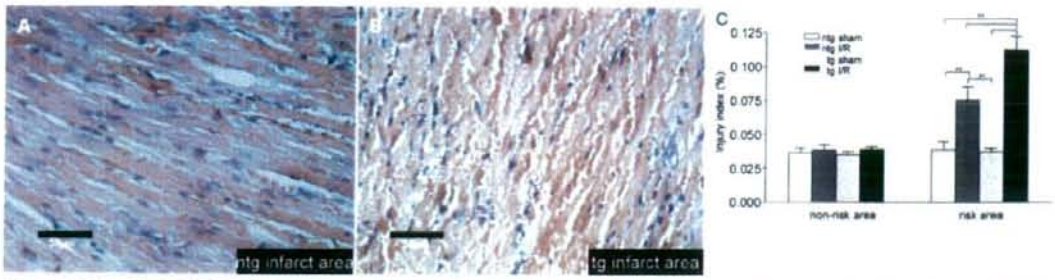

Figure 3. Effect of endothelial $CysLT_2R$ overexpression on myocardial histopathology and coronary endothelial permeability after acute I/R injury. **A** and **B**: Microscopic appearance of infarcted left ventricle in H&E-stained paraffin sections from ntg (**A**) and tg (**B**) mice 48 hours after acute I/R injury. **C**: Permeability of coronary endothelium to ^{125}I-BSA in the at-risk and nonrisk regions of the left ventricle of ntg and tg mice. $^{**}P < 0.01$; $n = 6$. Scale bars = 50 μm.

>100% increase in the number of infiltrating leukocytes in tg compared to ntg mice (1289 ± 113/mm^2 versus 528 ± 131/mm^2) (Figure 4).

Endothelial $CysLT_2R$ Overexpression Increases Egr-1, ICAM, and VCAM-1 Gene Expression in Transgenic Mouse Hearts

To examine potential molecular correlates for the I/R-induced histopathological and permeability alterations seen in tg mice, we determined myocardial mRNA expression of adhesion molecules ICAM and VCAM-1, as well as Egr-1 transcription factor (Figure 5). These genes have been implicated in the myocardial inflammatory response to I/R injury. No significant genotype-related differences were seen in basal expression of these genes. Myocardial expression of ICAM (Figure 5A), VCAM-1 (Figure 5B), and Egr-1 (Figure 5C) were increased significantly in both ntg and tg mice 3 hours after reperfusion. However, the I/R-induced increase in expression of these genes was greater in the tg mice (Figure 5).

Endothelial $CysLT_2R$ Overexpression Increases Cardiomyocyte Apoptosis in Transgenic Mouse Hearts

Because apoptosis plays a central role in myocardial cell loss after I/R, we determined whether endothelial overexpression of $CysLT_2R$ influences the number of apoptotic nuclei in cardiomyocytes in the peri-infarct region of tg and ntg mice after I/R. We found increased apoptosis of cells with cardiomyocyte morphology in both groups at 48 hours after reperfusion (Figure 6, A and B). However, F6
the number of apoptotic nuclei in the peri-infarct region of tg animals was significantly greater than in ntg animals (641 ± 222 TUNEL-positive myocytes/10^4 nuclei versus 84 ± 21/10^4 nuclei) (Figure 6B). At 48 hours after reperfusion, cardiomyocyte apoptosis was confined primarily to the peri-infarct region, although at earlier time points (ie, 6 to 24 hours after reperfusion), apoptosis is typically elevated in the infarct core. The number of apoptotic nuclei in the noninfarcted region was markedly lower than in the peri-infarct region and did not differ between ntg and tg mice (Figure 6B). It should be noted that apoptotic nuclei in noncardiomyocytes were observed; however, the precise cell types were not identified nor were they quantified in the present studies.

Endothelial $CysLT_2R$ Overexpression Accelerates Left Ventricular Remodeling after I/R

We used two-dimensional echocardiography to examine early (2 week) changes in LV wall and chamber dimensions after I/R. We chose the I/R model of myocardial infarction because it recapitulates some of the features of pathology after infarction seen in humans with reperfused MI, namely slow-developing LV remodeling that is generally complete by 3 to 6 weeks in rodents.[36,37] Repre-

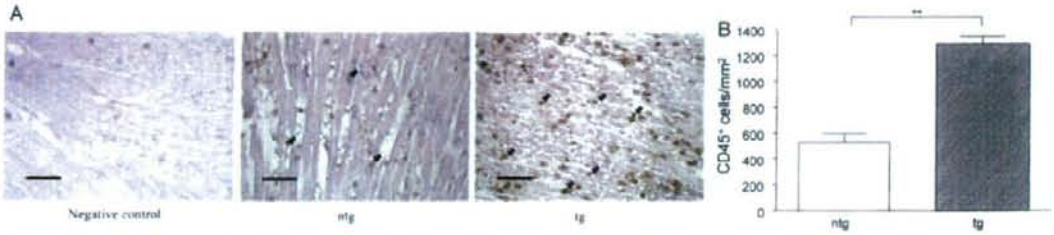

Figure 4. Effect of endothelial $CysLT_2R$ overexpression on leukocyte infiltration after I/R. **A**: Representative photomicrographs showing immunohistochemical detection of pan-leukocyte cell surface marker CD45 in the peri-infarct region of the LV in ntg and tg mice at 48 hours after reperfusion. **Arrows** indicate CD45-positive cells. **B**: Quantitative morphometric analysis of leukocyte infiltration. $^{**}P < 0.01$; $n = 4$. Scale bars = 50 μm. Original magnifications, ×400.

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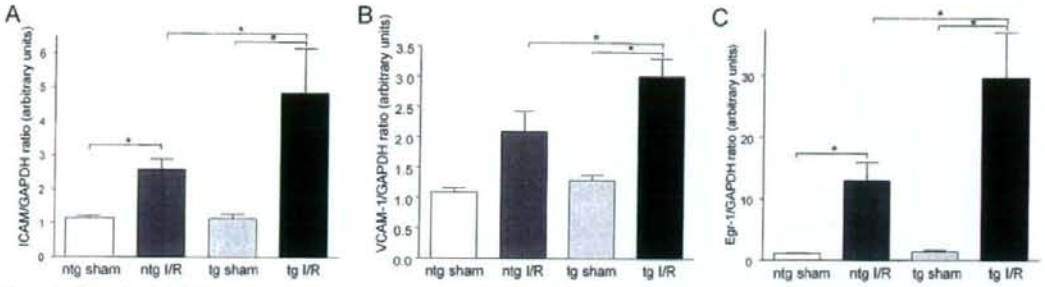

Figure 5. Effect of endothelial CysLT$_2$R overexpression on proinflammatory gene expression. **A–C:** Quantitative real-time PCR evaluation of ICAM (**A**), VCAM-1 (**B**), and Egr-1 (**C**) gene expression in total RNA extracted from the ischemic area of mouse hearts at 3 hours after reperfusion. $^*P < 0.05$; $n = 3$.

sentative M-mode frames taken before and 2 weeks after acute I/R injury are shown in Figure 7, and echocardiographic data are summarized in Table 1. Pre-I/R wall and chamber dimensions did not differ significantly between ntg and tg mice, with the exception of left ventricular diastolic dimension (LVDd) that was found to be slightly increased in tg mice (Figure 7, A and C; Table 1). Two weeks after reperfusion the tg mice presented significant thinning of the anterior wall/interventricular septum, whereas the anterior wall remained relatively unchanged in ntg mice (Figure 7, B and D; Table 1). Systolic and diastolic LV chamber dimensions after infarction remained relatively unchanged from preinfarction values in ntg mice (Figure 7, C and D; Table 1). However, tg mice showed a trend toward greater LV systolic dimension after infarction than ntg mice (21% versus 12% increase with respect to preinfarction values; Figure 7, A and B, and Table 1).

Endothelial CysLT$_2$R Overexpression Impairs Left Ventricular Function after I/R

We also assessed the effect of endothelial CysLT$_2$R overexpression on LV function using a microtip pressure catheter (Table 2). Basal LV function did not differ significantly between ntg and tg mice. Furthermore, both types of mice responded comparably to an acute bolus injection of dobutamine with increases in heart rate, LV pressures, and maximal and minimal values of the first derivative of LV pressure (Table 2). Two weeks after I/R, function remained relatively unchanged in ntg mice. In contrast, tg animals showed a trend toward decreased LV +dP/dt and LV −dP/dt and a significant increase in the time constant of isovolumic relaxation (τ), indicating the presence of both systolic and diastolic dysfunction (Table 2). Interestingly, both genotypes showed refractoriness of heart rate and LV pressures to dobutamine after infarction.

Discussion

The endothelium plays a pivotal role in maintaining vessel homeostasis by elaborating a variety of vasoactive, anti-inflammatory and antithrombotic factors that help maintain coronary vessel tone and protect the vessel wall against inflammatory cell and platelet adhesion.[38] Endothelial dysfunction plays a central role in the pathogenesis of myocardial I/R injury[1,5,18] and is characterized by impaired vessel relaxation, and enhanced expression of

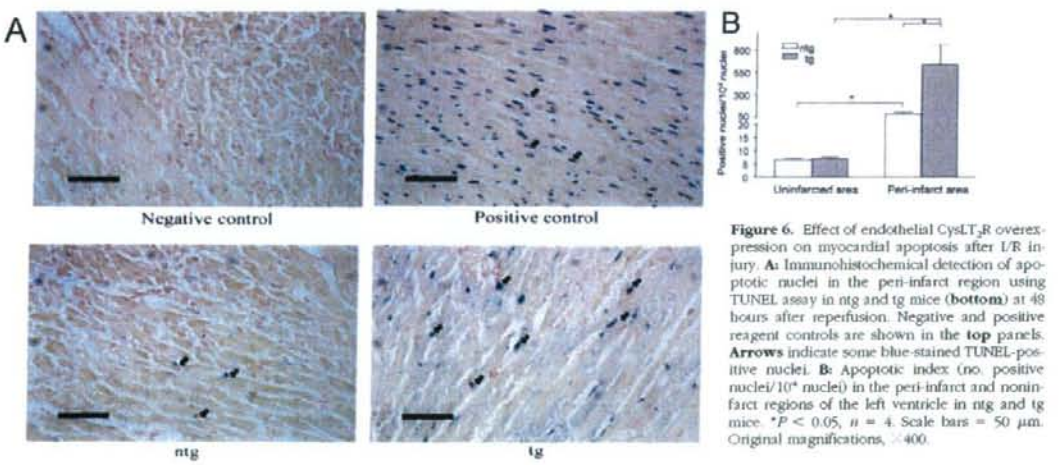

Figure 6. Effect of endothelial CysLT$_2$R overexpression on myocardial apoptosis after I/R injury. **A:** Immunohistochemical detection of apoptotic nuclei in the peri-infarct region using TUNEL assay in ntg and tg mice (**bottom**) at 48 hours after reperfusion. Negative and positive reagent controls are shown in the **top** panels. **Arrows** indicate some blue-stained TUNEL-positive nuclei. **B:** Apoptotic index (no. positive nuclei/10^4 nuclei) in the peri-infarct and noninfarct regions of the left ventricle in ntg and tg mice. $^*P < 0.05$, $n = 4$. Scale bars = 50 μm. Original magnifications, ×400.

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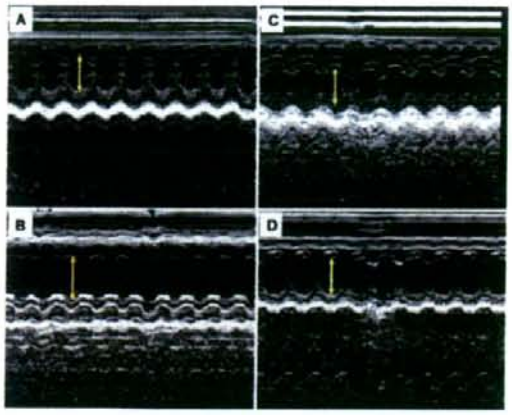

Figure 7. Effect of endothelial $CysLT_2R$ overexpression on left ventricular wall and chamber dimensions. **A–D:** Representative M-mode frames from the mid-papillary region of tg (**A**, **B**) and ntg (**C**, **D**) before (**A**, **C**) and 2 weeks after (**B**, **D**) acute I/R injury. **Arrow** indicates width of the LV chamber.

inflammatory and adhesion molecules, leading to increased vascular permeability, inflammatory cell infiltration, and platelet adhesion and thrombus formation.[3] CysLTs are major inflammatory mediators and activation of endothelial $CysLT_2R$ markedly increases vascular permeability in transgenic mice.[16] We now report that myocardial injury in response to acute I/R is exacerbated in endothelium-targeted $CysLT_2R$ transgenic mice, in association with increased coronary vascular permeability, inflammatory cell infiltration, and heightened myocyte loss through apoptosis.

CysLT synthesis increases in humans[20] with myocardial infarction. Furthermore, pretreatment with leukotriene biosynthesis inhibitors, AA-861 or Bay X1005, reduces neutrophil influx and infarct size after I/R injury in rats[39] and rabbits,[40] respectively, and intravenous infusion of a CysLT receptor antagonist LY-171883 at reperfusion decreases infarct size and improves LV functional recovery after myocardial infarction in cats.[41] In addition, recent linkage analysis studies revealed increased risk of stroke and myocardial infarction in some ethnic groups harboring a distinct haplotype in the *ALOX5AP* gene encoding 5-lipoxygenase-activating protein.[42] Thus, it is plausible in the current study that CysLTs released from resident and/or circulating inflammatory cells or synthesized by transcellular pathways between interacting neutrophils and endothelial cells[40,43] may activate $CysLT_2Rs$ in vascular endothelium to promote endothelial leakage and subsequent myocardial damage. CysLTs influence the adhesion of neutrophils to endothelium by up-regulating adhesion molecules[44,45] and may also act as chemotactic factors in recruitment of leukocytes to the infarcted myocardium. There is compelling evidence that activation of $CysLT_2R$ in cultured human endothelial cells leads to activation of a distinct set of immediate-early gene signatures[46] including the transcription factor Egr-1 and a variety of signaling and adhesion molecules that have been shown to participate in ischemic stress and reperfusion injury in mice.[47] In agreement with these findings, the expression of Egr-1, as well as ICAM and VCAM-1 genes, were elevated in the present study after activation of the human transgene in vascular endothelium, suggesting that they may contribute to the enhanced endothelial permeability and neutrophil infiltration in the infarcted myocardium of tg mice.

To examine the relative impact of transgenic endothelial overexpression of $CysLT_2$ receptor vis-à-vis mice native $CysLT_2$ expression after I/R, a number of tests were performed including analysis of the expression level of $CysLT_1$ and $CysLT_2$ receptors before and after injury (Figure 1), as well as comparative analysis of treatment with the dual $CysLT_1/CysLT_2$ receptor antagonist Bay-u9773, combined with infarction analysis of 5LO/leukotriene-deficient mice (Figure 2). Real-time PCR analysis indicated low levels of native murine $CysLT_1$ and $CysLT_2$ receptors in sham-operated mouse hearts and early after I/R (3 hours) with significantly higher levels of both receptors 48 hours after I/R. We speculate that the increased $CysLT_1R$ levels at 48 hours of I/R are attributable to infiltrating mononuclear leukocytes, a predominant cell type at this time point[32] and cells known to express this receptor subtype.[48] Based on the blue X-gal/LacZ staining in heart tissue as a surrogate for $CysLT_2R$ expression, enhanced expression of this receptor subtype after 48 hours of I/R in the infarct and peri-infarct zones was observed (Figure 1). Although the specific cell types expressing the induced receptor were not positively identified, several cell types including vascular smooth muscle[12] and endothelial cells,[15] Purkinje conducting cells,[11]

Table 1. Two-Dimensional Echocardiographic Analysis of Left Ventricular Wall and Chamber Dimension before and 2 Weeks after Acute Myocardial I/R in $CysLT_2R$ Transgenic and Nontransgenic Mice

	Pre-ischemia/reperfusion		Post-ischemia/reperfusion		% change from pre I/R	
	ntg	tg	ntg	tg	ntg	tg
LVDd (mm)	0.350 ± 0.010	0.389 ± 0.0120*	0.378 ± 0.0087	0.424 ± 0.0300	8.6 ± 4.4	8.8 ± 6.5
LVDs (mm)	0.200 ± 0.0090	0.229 ± 0.0173	0.220 ± 0.0185	0.27 ± 0.0342	11.5 ± 10.2	20.9 ± 15.9
IVSd (mm)	0.0751 ± 0.0030	0.0707 ± 0.0022	0.0727 ± 0.0025	0.0712 ± 0.0008	−2.6 ± 4.0	1.3 ± 3.8
IVSs (mm)	0.127 ± 0.0047	0.125 ± 0.0083	0.118 ± 0.0085	0.103 ± 0.0067†	−6.1 ± 8.8	−16.9 ± 4.3
PWd (mm)	0.0719 ± 0.0017	0.0763 ± 0.0044	0.0811 ± 0.0045	0.0867 ± 0.0041	13.9 ± 8.4	16.7 ± 11.2
PWs (mm)	0.124 ± 0.0052	0.125 ± 0.0044	0.143 ± 0.0148	0.148 ± 0.0060†	15.9 ± 11.4	19.6 ± 7.6
HR (bpm)	472 ± 17	479 ± 30	476 ± 21	481 ± 40	1.2 ± 4.9	0.30 ± 4.6

LVDd, left ventricular chamber diameter at diastole; LVDs, left ventricular chamber diameter at systole; IVSd, interventricular septum thickness at diastole; IVSs, interventricular septum thickness at systole; PWd, posterior wall thickness at diastole; PWs, posterior wall thickness at systole; HR, heart rate. *$P < 0.05$, tg versus ntg by unpaired *t*-test; †$P < 0.05$, pre-I/R versus post-I/R by paired *t*-test.

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Table 2. Left Ventricular Function in Control CysLT$_2$R-Transgenic and Nontransgenic Mice and 2 Weeks after Acute Myocardial I/R Injury

	ntg				tg			
	Control (n = 6)		I/R (n = 5)		Control (n = 5)		I/R (n = 5)	
	Before DB	After DB	Before DB	After DB	Before DB	After DB	Before DB	After DB
Heart rate, beats/minute	633 ± 14	709 ± 17*	616 ± 26	664 ± 44	575 ± 13‡	642 ± 11*‡	519 ± 32‡	522 ± 39†‡
LV function								
LV peak pressure, mmHg	71 ± 2	138 ± 13*	69 ± 4	72 ± 3	74 ± 4	130 ± 14*	70 ± 4	83 ± 8
LVESP, mmHg	70 ± 2	138 ± 13*	68 ± 4	71 ± 3	72 ± 4	130 ± 14*	70 ± 4*	83 ± 8†
LVEDP, mmHg	3. ± 0	5 ± 1	3 ± 0.3	4 ± 0.4	5 ± 1	7 ± 1*	4 ± 0.6	4 ± 0.2
LV +dP/dt, mmHg/second	5636 ± 320	16,046 ± 1281*	6409 ± 425	9952 ± 1557*†	6571 ± 604	13,921 ± 1867*	4896 ± 569	7412 ± 1728†
LV −dP/dt, mm Hg/second	−6058 ± 423	−10,377 ± 648*	−6624 ± 489	−6454 ± 397†	−6267 ± 621	−9144 ± 680*	−4865 ± 662	−5370 ± 735†
τ, ms	6.37 ± 0.44	5.10 ± 0.19*	5.91 ± 0.33	4.94 ± 0.17*	5.76 ± 0.22	5.77 ± 0.20‡	7.91 ± 0.82†	7.17 ± 0.77‡

DB, dobutamine; LV, left ventricle; LVESP, left ventricular end-systolic pressure; LVEDP, left ventricular end-diastolic pressure; LV +dP/dt, maximal value of the first derivative of LV pressure; LV −dP/dt, minimal value of the first derivative of LV pressure; τ, time constant for isovolumic relaxation.
*P < 0.05 after DB versus before DB; †P < 0.05, control versus I/R; ‡P < 0.05 tg versus ntg.

mesenchymal stem cells, and perhaps some leukocytes are possible candidates.

Bay-u9773 is a nonspecific antagonist of CysLT$_1$R and CysLT$_2$R, rendering it difficult to determine the precise contributions of each receptor subtype to ischemic injury. This is further complicated by the recent discovery of a third CysLT receptor subtype termed GPR17, that can bind CysLT$_1$R antagonists and was found to participate in focal rat brain ischemic injury.[10] Therefore, depending on the organ and tissue-specific vascular beds, various CysLT receptor subtypes might contribute to inflammatory vascular permeability changes in ischemic injury. In our studies, absence of leukotriene ligand to CysLT$_2$R, as represented in 5LO-deficient mice, and in preliminary studies with the recently acquired CysLT$_2$R-deficient LacZ mice (n = 3, data not shown), lack of ligand/receptor did not significantly influence myocardial injury compared to ntg mice. These data are consistent with those in a recent study showing that I/R injury did not differentially affect infarct size in 5LO-deficient mice compared to wild-type controls[49] but apparently not in agreement with the studies mentioned above with leukotriene biosynthesis inhibitors.[39,40] Moreover, the finding that Bay-u9773 did not reduce infarct size below baseline levels in ntg mice suggests that endogenous CysLT$_2$R does not play a significant role in I/R injury in contrast to the transgenic overexpression of the receptor. However, the observation that I/R induces murine CysLT$_2$R in our study at 48 hours, along with a recent report examining CysLT$_2$R expression in human brain tissue finding increased expression in microvascular endothelium after traumatic injury,[50] warrants further study to examine the pathophysiological sequelae of induction of CysLT$_2$R.

The mechanism by which endothelial CysLT$_2$R overexpression leads to increased myocyte apoptosis is not known. To our knowledge no direct role of CysLT$_2$R in cardiomyocyte apoptosis has been established. The cascade of events leading to myocyte apoptosis during I/R involves the activation of both the intrinsic mitochondrial proapoptotic pathway as well as the extrinsic pathway mediated by cytokine activation of death receptors.[51] Myocytes are particularly prone to apoptosis during reperfusion,[52] where up to 30% in the risk area may undergo apoptosis in the first few hours after reperfusion. The events of reperfusion that lead to cardiomyocyte apoptosis have not been fully elucidated. However, reactive oxygen species and cytokines produced by infiltrating inflammatory cells appear to play a central role in activating apoptotic pathways in myocytes.[52,53] For example, genetic mouse models harboring deletions of tumor necrosis factor-α and CD18 genes show reduced infarct size in response to I/R in association with decreased neutrophil infiltration, whereas null mice for the anti-oxidant gene heme oxygenase-1 have increased infarct size and reduced LV recovery in parallel with a decrease in antioxidant load.[52] In the current study, the enhanced influx of CD45$^+$ leukocytes, presumably mostly neutrophils, after reperfusion in CysLT$_2$R tg mice could potentially contribute to the enhanced myocyte apoptosis seen in these animals by a similar mechanism; however, additional mechanisms may also be at play. Regardless of mechanism, the increased apoptosis in tg mice would predictably lead to greater long-term loss of myocardial contractile mass, resulting in LV chamber remodeling and impairment of contractile function. Indeed, in the current study, CysLT$_2$R mice show accelerated LV remodeling, highlighted by decreased anterior wall thickness and increased LV systolic dimensions 2 weeks after reperfusion. Typically, LV remodeling in mice with reperfused myocardium is slow and often absent,[37]

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unless a significant amount of the LV (>40% of the AAR) is infarcted. Our results indicate that tg $CysLT_2R$ mice had significantly larger infarcts than the ntg counterparts. We presume that the heightened apoptosis is, at least partially, responsible for the larger infarct sizes and subsequent LV remodeling in these mice.

As expected, LV remodeling in tg mice was accompanied by impaired LV function after reperfusion. We believe that this is directly attributable to the greater myocyte loss in tg mice, because basal LV function and responsiveness to β-adrenergic stimulation did not differ significantly between the two groups of animals. In contrast, ntg mice were able to preserve LV function after reperfusion because of the significantly smaller infarcts and absence of negative remodeling. Interestingly, both genotypes showed marked refractoriness to dobutamine after reperfusion. The mechanism underlying this lack of response appears to be unrelated to $CysLT_2R$ overexpression, because it is also present in ntg controls. β-Adrenergic receptor desensitization usually occurs after myocardial infarction as the sympathetic nervous system attempts to maintain hemodynamic homeostasis. However, desensitization usually occurs throughout a longer time course than in the current studies, and is unlikely to be the explanation for the postreperfusion refractoriness to dobutamine.

In summary, the results of the current study indicate that endothelial-targeted overexpression of $CysLT_2R$ exacerbates myocardial injury after ischemia/reperfusion in association with increased inflammatory cell infiltration and cardiomyocyte apoptosis. Inhibition of endothelial $CysLT_2R$ activity should be explored further as a potential strategy for myocardial protection.

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Immunomodulation by n-3- versus n-6-rich lipid emulsions in murine acute lung injury—Role of platelet-activating factor receptor

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Objective: **Cytokines, platelet-activating factor (PAF), and eicosanoids control local and systemic inflammation. Conventional soybean oil-based lipid emulsions used for parenteral nutrition may aggravate the leukocyte inflammatory response or adhesion to the vessel wall. Fish oil-based lipid emulsions, in contrast, may exert an anti-inflammatory effect.**

Design: **We investigated the impact of lipid emulsions on leukocyte invasion, protein leakage, and cytokines in two murine models of acute inflammation.**

Setting: **Research laboratory of a university hospital.**

Subjects: **Wild-type mice and PAF-receptor knockout mice.**

Interventions: **Mice received an infusion of normal saline, fish oil- or soybean oil-based lipid emulsions before lipopolysaccharide challenge.**

Measurements and Main Results: **Preinfusion with soybean oil resulted in increased leukocyte invasion, myeloperoxidase activity, and protein leakage and exaggerated release of tumor necrosis factor (TNF)-α as well as macrophage inflammatory protein (MIP)-2 into the alveolar space after intratracheal lipopolysaccharide challenge. In contrast, preinfusion with fish oil reduced leukocyte invasion, myeloperoxidase activity, protein leakage, and TNF-α as well as MIP-2 generation. Corresponding profiles were found in plasma following intraperitoneal lipopolysaccharide application: Soybean oil increased but fish oil decreased the TNF-α and MIP-2 formation. When PAF-receptor-deficient mice were challenged with lipopolysaccharide, leukocyte invasion, lung tissue myeloperoxidase, cytokine generation, and alveolar protein leakage corresponded to those observed in wild-type animals. Fish oil and soybean oil lost their diverging effects on leukocyte transmigration, myeloperoxidase activity, leakage response, and cytokine generation in these knockout mice. Similarly, the differential impact of both lipid emulsions on these lipopolysaccharide-provoked changes was suppressed after pretreating animals with a PAF-receptor antagonist.**

Conclusions: **Fish oil- vs. soybean oil-based lipid infusions exert anti- vs. proinflammatory effects in murine models of acute inflammation. The PAF/PAF-receptor-linked signaling appears to be a prerequisite for this differential profile. (Crit Care Med 2007; 35:544–554)**

Key Words: platelet-activating factor; fish oil; lipid emulsions; inflammation; sepsis; acute lung injury

Acute lung injury, the systemic inflammatory response syndrome, and sepsis are common in intensive care patients (1, 2). At early time points, all three entities are associated with an excessive inflammatory response (3), but in later stages of systemic inflammatory response syndrome or sepsis, a reduced immune response may be detected, termed compensatory anti-inflammatory response syndrome (4). Lipids, lipid mediators, and inflammation are closely interrelated (3, 5). The generation of pro- and anti-inflammatory as well as vasoactive eicosanoids (such as prostaglandin E_2, prostaglandin I_2, and thromboxane A_2) is coupled to the generation of free arachidonic acid from phospholipids. In the context of lipids and inflammation, eicosanoids represent a major focus of interest due to their strong proinflammatory and anti-inflammatory potencies (3). Among the n-6 fatty acids in the Western diet and current nutritional regimes applied in intensive care units, linoleic acid is the most prominent fatty acid, giving rise to its elongation and desaturation product and eicosanoid precursor arachidonic acid. The n-3 fatty acids, including eicosapentaenoic acid and docosahexaenoic acid, make up an appreciable part of the fat in cold-water fish and seal meat. Eicosapentaenoic acid-derived 5-series leukotrienes generated by the 5-lipoxygenase and the cyclooxygenase product thromboxane A_3 possess markedly reduced inflammatory and vasomotor potencies compared with the arachidonic acid-derived lipid mediators and may even exert antagonistic functions (6).

In addition to acting as a precursor for eicosanoid formation, n-3 vis-à-vis n-6 fatty acid incorporation into membrane

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Drs. Schaefer and Ott contributed equally to the work and share first authorship. This article includes portions of the doctoral thesis of Juliane Ott.

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(phospho)-lipid pools was suggested to influence lipid-related intracellular signaling events (7). Subclasses of phosphatidylcholine such as the platelet-activating factor (PAF)-precursor pool, as well as phosphatidylinositol and sphingomyelin pools, may be particularly relevant in this respect. Next, gene transcription is modulated as nuclear translocation of nuclear factor-κB and is inhibited by n-3 fatty acids involving signaling by plasma membrane translocation and activation of protein kinase C (8). Furthermore, research work has linked a specific genetic background to the reduction in proinflammatory cytokine generation in volunteers (9).

PAF is a major lipid mediator derived in two steps from phosphatidylcholine yielding free arachidonic acid and the active mediator (10). Furthermore, PAF-like molecules may be generated by oxidative attack on unsaturated fatty acids in phosphatidylcholine, which may aggravate sepsis and tissue injury (11). PAF promotes adhesion of leukocytes to endothelial cells, and application of PAF-receptor antagonists (PAF-RA) ameliorates features of sepsis and shock in experimental models (12), but effects on mortality in septic patients were not reported in clinical phase III studies (13, 14). Mice carrying a targeted disruption of the PAF-receptor (PAF-R) gene exhibit an ameliorated response to an acid-aspiration lung injury model; however, they remain sensitive to lipopolysaccharide (LPS) and endotoxin-induced shock (15).

Different groups reported a major influence of nutrition including n-3 fatty acids on morbidity of intensive care patients. In the adult respiratory distress syndrome, a tailored nutrition with eicosapentaenoic acid, γ-linoleic acid, and antioxidants was reported to improve oxygenation, reduce length of mechanical ventilation, decrease incidence of new organ failures, and shorten length of stay in the intensive care unit (16). Using fish oil supplements, however, several days to weeks are required to effectively influence the fatty acid composition of membrane (phospho)-lipids and thereby the lipid mediator profile in humans (17). In contrast, when administering a fish oil-based lipid emulsion via the intravenous route in volunteers or septic patients, we recently demonstrated rapid changes in cell membrane fatty acid composition and leukocyte functions (18, 19).

In the present study, we developed a murine model suitable for continuous long-term intravenous lipid infusions and subsequently submitted mice to intratracheal or intraperitoneal LPS injection. In addition to analyzing systemic cytokine generation, we focused on compartmentalized inflammatory events such as cytokine appearance in the bronchoalveolar space and recruitment of leukocytes to the alveolar compartment.

MATERIALS AND METHODS

Reagents. Lipoven 10% (soybean oil, or SO) and Omegaven 10% (fish oil, or FO) were purchased from Fresenius-Kabi (Bad Homburg, Germany). Analysis of fatty acid composition of the lipid emulsions is given in Table 1. Chemicals of highest purity were obtained from Merck (Darmstadt, Germany). LPS (O111:B4) from *Escherichia coli* was from Sigma-Aldrich (Dreisenhofen, Germany). The PAF antagonist BN52021 originated from Biomol (Hamburg, Germany).

Animals. Local government authorities and university officials responsible for animal protection approved the study. Parent and offspring PAF-R −/− mice on the BALB/c background and wild-type animals (WT) were kept under standard conditions with a 12-hr day/night cycle under specific pathogen-free conditions. Animals 8–12 wks old (18–21 g weight) were used for experiments. For implantation of a jugular vein catheter, mice were anesthetized by an intraperitoneal injection of a 1:1 mixture of xylazine at 80–100 mg per kilogram of body weight (Bayer, Leverkusen, Germany)/ketamine (Pharmacia & Upjohn, Erlangen, Germany). When animals were anesthetized and spontaneously breathing, points of incisions were shaved and disinfected. A silicon catheter (Braun, Melsungen, Germany) was inserted into the left jugular vein and tied.

Table 1. Fatty acid composition of the soybean oil (SO)-based and fish oil (FO)-based lipid-emulsion (g/L)

Fatty Acid	SO	FO
C14:0	—	4.9
C16:0	12.4	10.7
C16:1n-7	—	8.2
C18:0	5.0	2.4
C18:1n-9	24.1	12.3
C18:2n-6	52.2	3.7
C18:3n-3	8.2	1.3
C20:4n-6	—	2.6
C20:5n-3	—	18.8
C22:5n-3	—	2.8
C22:6n-3	—	16.5
Others	—	16.1

The SO-based emulsion (Lipoven) and the FO-based lipid emulsion (Omegaven) were manufactured with identical techniques and additives. Repetitive gas chromatographic controls of both lipid emulsions revealed <0.3% free eicosapentaenoic acid or arachidonic acid as related to the esterified amounts of these fatty acids.

The catheter was tunneled to the neck of the animal and connected to an osmotic minipump (Alzet, Cupertino, CA) filled with NaCl 0.9% situated in an external device tied to the back allowing easy access and exchange of pumps without anesthesia.

Murine Model of Acute Lung Injury. Mice were anesthetized with xylazine/ketamine, a small catheter was inserted in the trachea, and LPS (0, 1, or 10 μg in 50 μL of normal saline/mouse) was instilled. Twenty-four hours after LPS application, mice were killed by an overdose of isoflurane (Abbot, Wiesbaden, Germany), and bronchoalveolar lavage (BAL) was performed as described (20). An additional BAL was performed after 4 hrs in mice receiving 10 μg of LPS as a precaution since the escalation in LPS dose could have increased mortality in the model. However, even after receiving the higher dose of LPS, all animals survived the observation period. Alveolar-recruited leukocytes recovered from lungs of LPS-challenged and control mice were counted in a counting chamber. Differentiation of leukocytes in blinded fashion was done on differential cell counts of Pappenheim-stained cytocentrifuge preparations, using overall morphologic criteria, including differences in cell size and shape of nuclei. Protein in bronchoalveolar lavage was determined according to Lowry et al (21).

Model of Intraperitoneal Inflammation. Mice were anesthetized with xylazine/ketamine, and LPS (2 μg/mouse) or vehicle was injected intraperitoneally. For cytokine measurements from plasma and white blood cell count in peripheral blood, mice were exsanguinated 2 hrs after LPS treatment in deep anesthesia.

Enzyme-Linked Immunosorbent Assay. Cytokine enzyme-linked immunosorbent assays for tumor necrosis factor (TNF)-α and macrophage inflammatory protein (MIP)-2 were performed according to the manufacturer's (R&D, Wiesbaden, Germany) instructions.

Myeloperoxidase Assay. Lung myeloperoxidase (MPO) was determined as an index of tissue neutrophil accumulation 24 hrs after LPS challenge as described (22). After weighing of lung stored at −80°C, the frozen lung was homogenized, sonicated, and centrifuged at 25,000 × *g*. MPO activity was calculated from change in absorbance (460 nm) resulting from decomposition of H_2O_2 in the presence of o-dianisidine.

Wet-to-Dry Ratio. To assess pulmonary edema, determination of lung wet weight was performed after removal of extraneous bronchial and cardiac structures as described (23). To measure dry weight, lungs were incubated in a drying oven a week at 80°C and then reweighed.

Peripheral White Blood Cell Counts. White blood count of peripheral blood was measured as previously described (24).

Experimental Protocol. Seven days after central venous catheter implantation in mice, exchange of pumps was performed. Then, 200 μL per day of either SO, FO, or 0.9% NaCl was infused over 3 days with the mice being al-

lowed access to water and chow *ad libitum*. The amount of lipids infused is equivalent to 1.0 g/kg/day. However, the energy expenditure of mice is nearly three times higher that that of humans. Therefore, the infused lipids were considered to be close to lower limits of recommended amount of lipids in parenteral nutrition. While receiving infusions, mice were subjected to low-dose unfractionated heparin injected subcutaneously. In experiments with WT mice treated with PAF-RA, 10 mg/kg of body weight BN52021 (Biomol, Hamburg, Germany) was injected into the tail vein 30 mins before intratracheal LPS application.

Statistics. Data are given as the mean ± SEM. Two-way analysis of variance was performed to test for differences between different infusion groups and mice strains (WT, PAF-R −/−, PAF-RA). *Post hoc* analysis was carried out using Student-Newman-Keuls' test. As data of protein in lavage and leukocytes in BAL (1 μg, 24 hrs) were not normally distributed, log-transformation was performed. Wet-to-dry ratios between unstimulated and stimulated groups were compared using Student's *t*-test. Probability (p) values $<.05$ were considered to indicate statistical significance. Analysis was carried out using SigmaStat.

RESULTS

Effect of Lipid Emulsions on Alveolar Leukocyte Recruitment and Wet-to-Dry Ratio in LPS-Induced Acute Lung Injury. Without LPS challenge, we found $0.10 \pm 0.01 \times 10^6$ leukocytes in the BAL fluid without significant variation between NaCl and lipid infusion groups. After stimulation of WT mice with 1 μg of LPS, leukocytes migrated into the alveolar space, with their numbers in BAL fluid rising to $1.09 \pm 0.08 \times 10^6$ cells after 24 hrs (Fig. 1*A*). Preinfusion of SO massively increased leukocyte recruitment by nearly 100% ($p < .01$ vs. NaCl). In contrast, in mice receiving FO, leukocytes were significantly reduced to <60% ($p < .01$ vs. SO and NaCl). When using 10

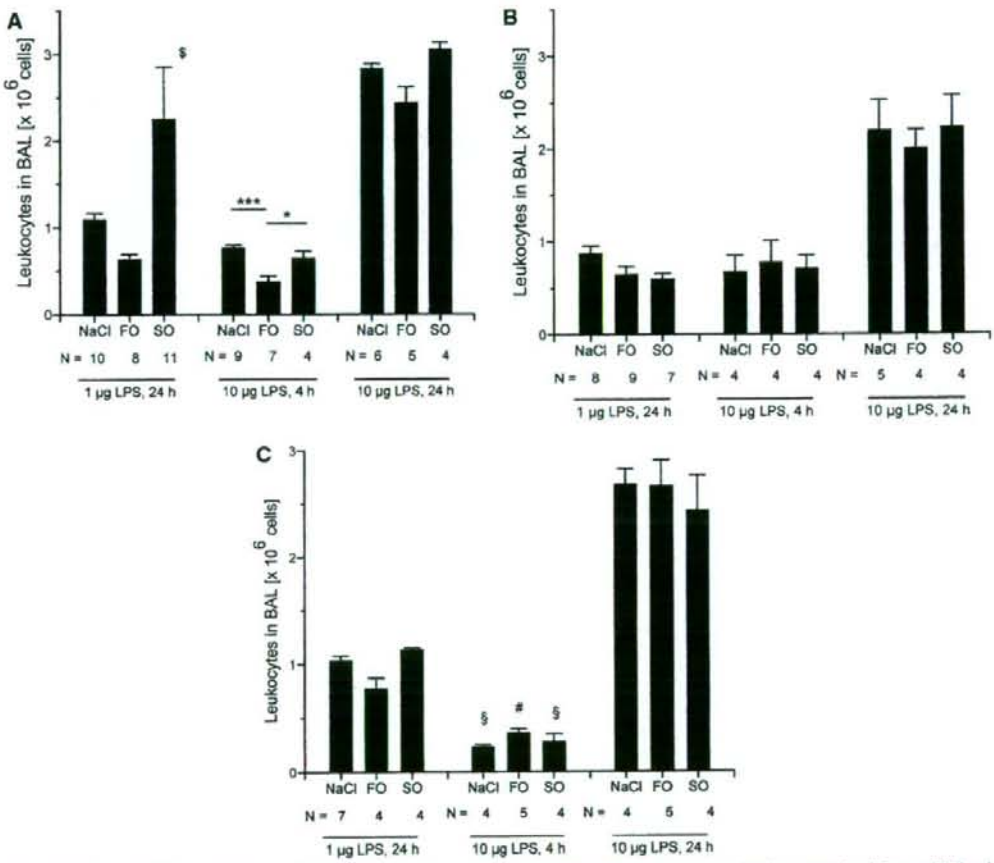

Figure 1. Impact of fish oil (*FO*)- vs. soybean oil (*SO*)-based lipid infusions on leukocytes migrated into the alveolar space in wild-type (WT) mice, mice lacking the platelet-activating factor-receptor (PAF-R −/−), and WT mice treated with platelet-activating factor receptor antagonist (PAF-RA) in a model of acute lung injury. WT mice (*A*), PAF-R −/− mice (*B*), and WT mice treated with a PAF-RA (*C*) were infused with saline (*NaCl*) or FO- or SO-based lipid emulsions, followed by application of 1 or 10 μg of endotoxin (lipopolysaccharide, LPS) intratracheally 4 or 24 hrs before performing a bronchoalveolar lavage (*BAL*). Total lavage leukocyte counts are given. Only in WT mice, a significant difference of SO- vs. FO-based lipid emulsions, and of saline (control) vs. FO-based lipid emulsion, respectively, was detectable ($\$p < .01$ all groups differed significantly from each other; $*p < .05$ FO vs. SO; $***p < .001$ FO vs. control). Animals exposed to 10 μg of LPS for 4 hrs in the PAF-RA groups exhibited a reduction of leukocyte numbers ($\S p < .05$ vs. WT and PAF-R −/−; $\#p < .05$ vs. PAF-R −/−). Data are given as mean ± SEM. Numbers of animals per group are detailed below columns. Error bars are missing when falling into symbol.

μg of LPS in the normal saline group, we found $0.76 \pm 0.04 \times 10^6$ leukocytes after 4 hrs rising to $2.83 \pm 0.06 \times 10^6$ leukocytes after 24 hrs in the BAL. After 4 hrs, infusion of FO-based lipid emulsions induced a significant reduction of transmigrated leukocytes by nearly 50% ($p < .001$ vs. NaCl and $p < .05$ vs. SO), whereas SO had no impact on leukocyte invasion compared with NaCl. After 24 hrs in mice receiving SO, leukocyte invasion was comparable to mice receiving NaCl, whereas infusions of FO-based lipids led to a small reduction.

Without LPS challenge, differential count of leukocytes in BAL was 2.5 ± 0.8% granulocytes, 97.0 ± 0.9% monocytes/macrophages, and 0.5 ± 0.3% lymphocytes without effect of lipid emulsions on this feature. At 24 hrs after challenge with 1 μg of LPS, 78.1 ± 3.2% granulocytes, 2.0 ± 0.4% lymphocytes, and 20.2 ± 3.1% monocytes/macrophages were detected in the BAL of WT mice receiving NaCl. This profile of predominant neutrophil invasion was not changed by infusion of lipids or LPS dose.

Wet-to-dry ratio was determined to evaluate degree of lung injury. Without LPS, wet-to-dry ratio was 4.62 ± 0.07 in control animals with both lipid infusions exhibiting no further impact. After instillation of 10 μg of LPS in mice receiving normal saline, wet-to-dry ratio increased to 5.12 ± 0.09 after 24 hrs ($p < .01$ vs. control) whereas both lipid emulsions did not modulate this feature and did not differ significantly from the NaCl group.

Significance of PAF-R for Recruitment of Leukocytes Into the Alveolar Space and Its Modulation by Lipid Emulsions. Bronchoalveolar lavage performed 4 or 24 hrs after intratracheal LPS challenge with 1 or 10 μg of LPS in PAF-R −/− mice submitted to infusion of normal saline (control) indicated a similar response as encountered in corresponding WT animals. Quantity (Fig. 1*B*) and cell differentiation of recruited leukocytes were not different in both strains. The diverging effect of preinfused lipid emulsions on alveolar recruitment of leukocytes was, however, fully lost in PAF-R −/− mice. In both lipid infusion groups, numbers of recruited leukocytes were slightly but not statistically significantly different compared with normal saline control mice. This finding was irrespective of LPS dose or time of lavage.

To confirm our results in PAF-R −/− mice, we treated WT mice with the PAF-RA BN52021. WT mice were infused for 3 days with normal saline (NaCl control) or with FO- or SO-based lipid emulsions followed by application of 1 or 10 μg/mouse LPS intratracheally 4 or 24 hrs before performing a BAL (Fig. 1*C*). A dose of 10 mg/kg BN52021 was injected into the tail vein 30 mins before LPS application. In mice treated with normal saline, the absolute leukocyte numbers and differential count in BAL did not differ from WT or PAF-R −/− mice 24 hrs after LPS challenge. However, 4 hrs after instillation of 10 μg of LPS, we found a strong reduction of leukocytes in all PAF-RA groups. The reduction was significant in animals receiving NaCl or SO compared with respective WT and PAF-R −/− groups ($p < .05$ for each comparison). In animals receiving FO, leukocytes were significantly lower compared with the FO-PAF-R −/− group ($p < .05$) but comparable to WT mice infused with FO-based emulsions.

As in PAF-R −/− mice, FO or SO no longer modulated the amount of alveolar recruited leukocytes after treatment with a PAF-RA. This was consistent irrespective of time of lavage and dose of LPS. In particular, in contrast to WT mice, SO-based lipid emulsions lost their capacity to double alveolar leukocyte transmigration.

LPS-Induced Accumulation of Neutrophils in Lung Tissue. MPO activity was measured before and 24 hrs after LPS challenge to assess neutrophil accumulation in lung tissue. In lungs of WT mice without LPS exposure, MPO activity was 0.9 ± 0.3 units/g without significant effect of lipid emulsions (Table 2). After instillation of 10 μg of LPS, MPO increased to 6.6 ± 0.7 units/g in control animals. After infusion of SO-based lipid emulsions, MPO was nearly two-fold higher compared with the FO and normal saline groups ($p < .05$ for each comparison). After application of 1 μg of LPS intratracheally, we found the same trend for MPO determination in WT animals, but results failed to reach the level of significance. The diverging effect of preinfused lipid emulsions on neutrophil accumulation in lung tissue was, however, lost in PAF-R −/− mice and after application of the PAF-RA in mice receiving 10 μg of LPS.

LPS-Induced Alveolar Protein Leakage. To examine the impact of lipids on lung injury, we determined protein in the BAL as marker for vascular leakage. In WT animals without LPS challenge, protein concentration was determined as 32 ± 3 μg/mL without significant modulation by lipid emulsions (Table 3). After intratracheal challenge with 1 μg or 10 μg of LPS, protein in BAL increased to 273 ± 16 μg/mL or 551 ± 34 μg/mL, respectively, after 24 hrs in WT animals. Infusion of FO significantly decreased alveolar protein leakage after 1 μg ($p < .01$ vs. NaCl and SO) and 10 μg of LPS, whereas after SO infusion protein concentrations slightly increased. Due to the marked reduction of protein in BAL after FO after 1 μg of LPS, FO-WT animals differed significantly from FO-PAF-R −/− mice ($p < .05$).

Generation of MIP-2 After LPS Instillation. We then examined the impact of lipid emulsions on intra-alveolar cytokine generation in our model. Without LPS stimulation, MIP-2 concentration in BAL

Table 2. Myeloperoxidase activity in lung homogenates (units/g of tissue)

	Without LPS	1 μg of LPS (24 Hrs)	10 μg of LPS (24 Hrs)
Wild-type			
NaCl	0.9 ± 0.3 (n = 4)	3.3 ± 0.7 (n = 4)	6.6 ± 0.7 (n = 8)
FO	1.0 ± 0.4 (n = 4)	3.4 ± 0.4 (n = 4)	6.8 ± 1.4 (n = 4)
SO	0.9 ± 0.4 (n = 4)	5.1 ± 0.9 (n = 4)	11.3 ± 0.9 (n = 4)[a]
PAF-R −/−			
NaCl	0.8 ± 0.4 (n = 4)	ND	9.1 ± 1.0 (n = 4)
FO	0.9 ± 0.4 (n = 4)	ND	9.4 ± 1.4 (n = 4)
SO	0.9 ± 0.3 (n = 4)	ND	7.7 ± 0.5 (n = 4)
PAF-RA			
NaCl	0.9 ± 0.4 (n = 4)	ND	9.5 ± 1.5 (n = 4)
FO	0.8 ± 0.4 (n = 4)	ND	8.3 ± 0.4 (n = 4)
SO	0.9 ± 0.5 (n = 4)	ND	9.6 ± 1.6 (n = 4)

LPS, lipopolysaccharide; NaCl, saline; FO, fish oil; SO, soybean oil; PAF-R −/−, mice lacking the platelet-activating factor receptor; ND, not done; PAF-RA, platelet-activating factor receptor antagonist.

[a] $p < .05$ for comparison with NaCl and FO. Wild-type mice, PAF-R −/− mice, and wild-type mice treated with a PAF-RA were infused for 3 days with NaCl (control) or with FO- or SO-based lipid emulsions, followed by stimulation with 1 or 10 μg of endotoxin (LPS) intratracheally for 24 hrs.

Table 3. Protein concentration in bronchoalveolar lavage (μg/mL)

	Without LPS	1 μg of LPS (24 Hrs)	10 μg of LPS (24 Hrs)
Wild-type			
NaCl	32 ± 3 (n = 4)	273 ± 16 (n = 21)	551 ± 34 (n = 4)
FO	33 ± 4 (n = 4)	148 ± 21 (n = 6)[a,b]	416 ± 21 (n = 5)[c]
SO	31 ± 5 (n = 5)	313 ± 40 (n = 11)	641 ± 11 (n = 4)
PAF-R −/−			
NaCl	31 ± 4 (n = 4)	347 ± 36 (n = 11)	382 ± 89 (n = 6)
FO	33 ± 5 (n = 4)	338 ± 69 (n = 9)	462 ± 43 (n = 4)
SO	32 ± 5 (n = 4)	304 ± 67 (n = 7)	654 ± 115 (n = 5)
PAF-RA			
NaCl	33 ± 4 (n = 4)	325 ± 40 (n = 4)	552 ± 86 (n = 4)
FO	33 ± 3 (n = 4)	253 ± 50 (n = 4)	424 ± 102 (n = 6)
SO	32 ± 4 (n = 4)	331 ± 70 (n = 4)	527 ± 119 (n = 6)

LPS, lipopolysaccharide; NaCl, saline; FO, fish oil; SO, soybean oil; PAF-R −/−, mice lacking the platelet-activating factor receptor; PAF-RA, platelet-activating factor receptor antagonist.

[a]Within WT, $p < .01$ FO vs. NaCl and SO; [b]within FO infusion groups, $p < .05$ WT vs. PAF-R−/−; [c]within WT, $p < .05$ FO vs. SO. Wild-type mice (WT), PAF-R −/− mice, and WT mice treated with a PAF-RA were infused for 3 days with NaCl (control) or with FO-, or SO-based lipid emulsions, followed by stimulation with 1 or 10 μg of endotoxin (LPS) intratracheally for 24 hrs.

was below detection limit regardless of infusion used or mouse line examined. At 24 hrs after challenge with 1 μg of LPS, we found an increase in lavage MIP-2 concentration to 112 ± 6 pg/mL in mice infused with normal saline (Fig. 2*A*). In mice receiving SO, MIP-2 was similar compared with the NaCl group. However, in mice receiving FO, MIP-2 concentration was significantly reduced ($p < .001$ vs. NaCl and $p < .05$ vs. SO). When using 10 μg of LPS in the normal saline group, we found a tremendous increase in MIP-2 after 4 hrs to 1225 ± 96 pg/mL and a decline to 165 ± 18 pg/mL after 24 hrs. After 4 hrs, infusion of FO-based lipid emulsions induced a small reduction of MIP-2, but preinfusion with SO provoked a significant increase of nearly 25% compared with the NaCl group ($p < .05$ vs. FO or NaCl). After 24 hrs in mice receiving SO, MIP-2 concentration remained massively elevated (741 ± 73 pg/mL, $p < .001$ vs. NaCL or FO) and was reduced to 140 ± 18 pg/mL in the FO group.

In PAF-R −/− mice receiving normal saline, MIP-2 levels 24 hrs after challenge with 1 or 10 μg of LPS were comparable to WT animals. The MIP-2 concentrations in both lipid infusion groups did not differ significantly from each other and from saline control irrespective of time of lavage or dose of LPS (Fig. 2*B*). After 4 hrs in mice receiving 10 μg of LPS, MIP-2 concentrations were significantly higher compared with corresponding WT animals in the NaCl and FO groups ($p < .05$) but did not differ from the animals receiving SO.

To confirm our results in PAF-R −/− mice, we treated WT mice with the PAF-RA BN52021. At 24 hrs after challenge with 1 μg of LPS, PAF-RA pretreatment exhibited a reduction of MIP-2 down to about one third compared with WT and PAF-R −/− mice receiving normal saline (Fig. 2*C*, $p < .05$). This reduction by PAF-RA pretreatment was also found in mice receiving either lipid emulsion compared with WT and PAF-R −/− animals ($p < .05$).

Using 10 μg of LPS in the PAF-RA group, MIP-2 concentrations after 4 and 24 hrs were similar to the concentrations detected in WT and PAF-R −/− mice receiving NaCl. In contrast to WT animals, but similar to PAF-R −/−, application of PAF-RA abolished differential impact of FO vs. SO lipid infusions on intra-alveolar MIP-2 concentrations irrespective of dose of LPS or time of lavage. Due to the massive increase after infusion of SO-based lipid emulsions, WT animals differed significantly from PAF-R −/− and PAF-RA groups ($p < .01$).

TNF-α Concentration in BAL After LPS Challenge. Next, we examined impact of lipid emulsions on TNF-α concentration in BAL. Without LPS stimulation, TNF-α was undetectable in BAL in all groups irrespective of mouse line and infusion used. At 24 hrs after challenge with 1 μg of LPS, we found an increase in TNF-α concentration to 162 ± 12 pg/mL in mice infused with normal saline (Fig. 3*A*). In mice receiving SO, a similar TNF-α concentration was detected. In contrast, infusion of FO resulted in a significant reduction of TNF-α ($p < .05$ vs. NaCl and SO). After challenge with 10 μg of LPS in mice receiving normal saline, TNF-α concentration massively rose to 1496 ± 92 pg/mL after 4 hrs and to 564 ± 126 pg/mL after 24 hrs. After 4 hrs, infusion of SO led to a further small increase. In contrast, in the FO group, TNF-α was significantly reduced by nearly 25% compared with the NaCL group ($p < .05$ vs. NaCl and SO). However, in the BAL performed after 24 hrs, TNF-α concentration was not significantly modulated by lipid emulsions.

In PAF-R −/− mice receiving NaCl infusions, TNF-α was slightly lower after LPS challenge as compared with WT animals (Fig. 3*B*). TNF-α concentrations in the FO or SO group did not differ significantly from each other and from saline control irrespective of time of lavage or dose of LPS.

To confirm our results in PAF-R −/− mice, we treated WT mice with the PAF-RA BN52021. At 24 hrs after challenge with 1 μg of LPS, TNF-α concentration in PAF-RA-pretreated mice receiving NaCl was 100 ± 12 pg/mL, exhibiting a significant reduction by nearly 40% compared with saline-infused WT mice ($p < .05$, Fig. 3*C*). When instilling 10 μg of LPS, TNF-α concentrations after 4 and 24 hrs were similar to concentrations determined in WT and PAF-R −/− mice receiving normal saline. In contrast to WT animals, but similar to PAF-R −/−, injection of PAF-RA inhibited the differential impact of FO and SO lipid infusions on intra-alveolar TNF-α concentrations irrespective of dose of LPS or time of lavage.

After 4 hrs in mice stimulated with 10 μg of LPS, TNF-α concentrations were increased in all infusion groups receiving PAF-RA. In mice infused with FO, the PAF-RA mice differed significantly from the WT and PAF-R −/− animals ($p < .05$). As TNF-α was also increased in WT mice after SO infusion, the PAF-RA SO group and the WT SO group differed significantly from the PAF-R −/− mice ($p < .05$).

Cytokine Concentrations in Plasma After Intraperitoneal LPS Instillation. Next, we asked if lipid emulsions would have similar effects in a model of abdominal inflammation. In pilot experiments, we determined that TNF-α concentration in plasma peaked at 2 hrs after intra-abdominal LPS instillation in our model. Using the previous infusion setting, we challenged mice with 2 μg LPS intraperitoneally 2 hrs before kill and bleeding.

Before LPS challenge, leukocyte counts in peripheral blood were 6.6 ± 0.4 G/L

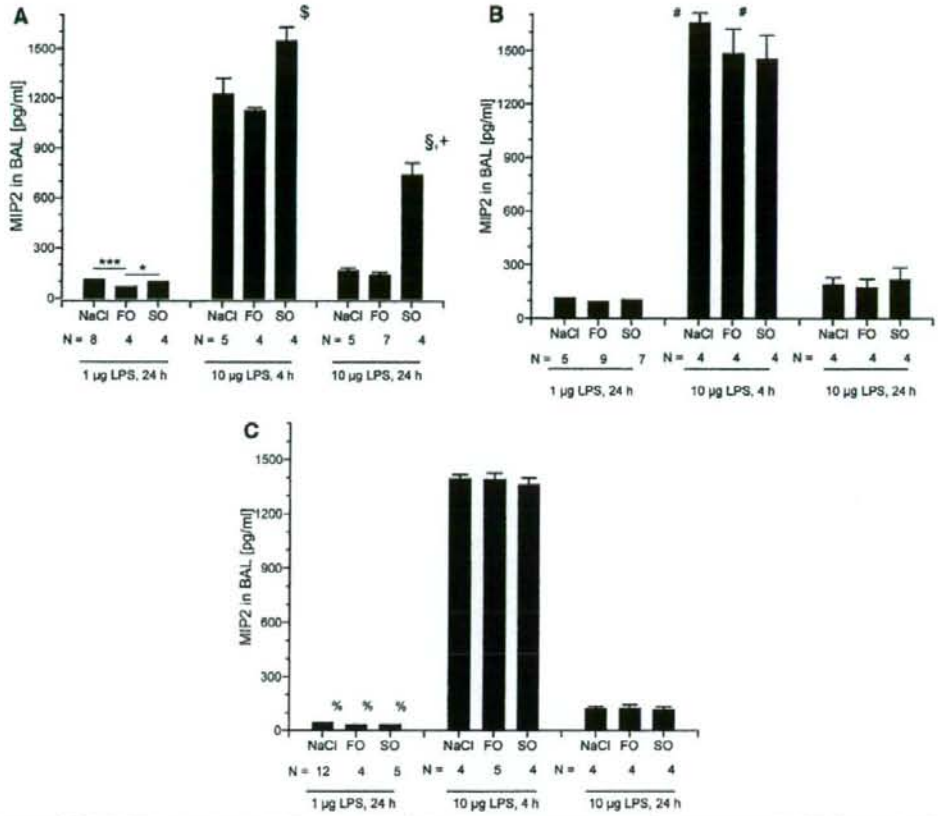

Figure 2. Impact of fish oil (*FO*)- vs. soybean oil (*SO*)-based lipid infusions on alveolar macrophage inflammatory protein (*MIP*)-2 generation in wild-type (WT) mice, mice lacking the platelet-activating factor-receptor (PAF-R −/−), and WT mice treated with platelet-activating factor receptor antagonist (PAF-RA) in a model of acute lung injury. WT mice (*A*), PAF-R −/− mice (*B*), and WT mice treated with a PAF-RA (*C*) were infused for 3 days with normal saline (control) or FO- or SO-based lipid emulsions, followed by stimulation with 1 or 10 µg of endotoxin (lipopolysaccharide, LPS) intratracheally 4 or 24 hrs before lavage. MIP-2 concentrations in bronchoalveolar lavage (*BAL*) were determined by enzyme-linked immunosorbent assay. Infusion of FO lipid emulsions resulted in decreased MIP-2 formation in WT mice (*$p < .05$ vs. SO; ***$p < .001$ vs. control). Infusion of SO resulted in increased MIP-2 generation compared with control and FO in both 10-µg groups ($p < .05; §$p < .001). In PAF-R −/− or in WT mice treated with PAF-RA, no significant impact of lipid emulsions could be detected. MIP-2 concentrations in PAF-R −/− mice receiving 10 µg of LPS were higher after 4 hrs compared with corresponding WT controls (#$p < .05$). After 24 hrs in WT-SO mice challenged with 10 µg of LPS, MIP-2 was significantly higher compared with the corresponding infusion groups of PAF-R −/− and PAF-RA mice (+$p < .01$). All infusion groups of PAF-RA mice receiving 1 µg of LPS were significantly lower than corresponding PAF-R −/− and WT groups (%$p < .05$). Data are given as mean ± SEM. Numbers of animals per group are detailed below columns. Error bars are missing when falling into symbol.

(n = 5) without significant impact of the lipid emulsions. Two hours after intraperitoneal LPS challenge, 7.5 ± 0.8 × 10^9/L leukocytes were found in peripheral blood in mice receiving normal saline (n = 4). After FO infusion, leukocytes were slightly lower and SO slightly increased peripheral leukocytes; however, no significant difference was found.

Before LPS instillation in PAF-R −/− mice, leukocyte counts in peripheral blood were slightly higher compared with WT mice (7.2 ± 0.5 × 10^9/L, n = 4). Again, no significant impact of the lipid emulsions was found. After LPS injection into the peritoneal cavity, we detected 7.9 ± 1.6 × 10^9/L leukocytes in mice receiving NaCl. After FO or SO treatment, 8.5 ± 1.8 × 10^9/L and 7.1 ± 1.9 × 10^9/L leukocytes were measured (n = 4 each). However, no significant difference was found between infusion regimes.

Before LPS stimulation, no MIP-2 was detectable in plasma in either group. In WT controls, LPS challenge induced an increase to 9.0 ± 1.9 ng/mL. Infusion of FO-derived lipid emulsions resulted in a diminished MIP-2 serum concentration, whereas application of SO-based lipids increased MIP-2 levels significantly compared with the FO group ($p < .05$, Fig. 4*A*). In PAF-R −/−, LPS stimulation induced a three-fold increase in MIP-2 concentrations compared with WT in mice receiving NaCl ($p < .01$). This increase was also detected in both lipid infusion groups; however, differences between the infusion groups were abolished (Fig. 4*B*). The increase in MIP-2 was significant comparing PAF-R −/− mice with WT animals receiving FO ($p < .01$) but not in mice infused with SO.

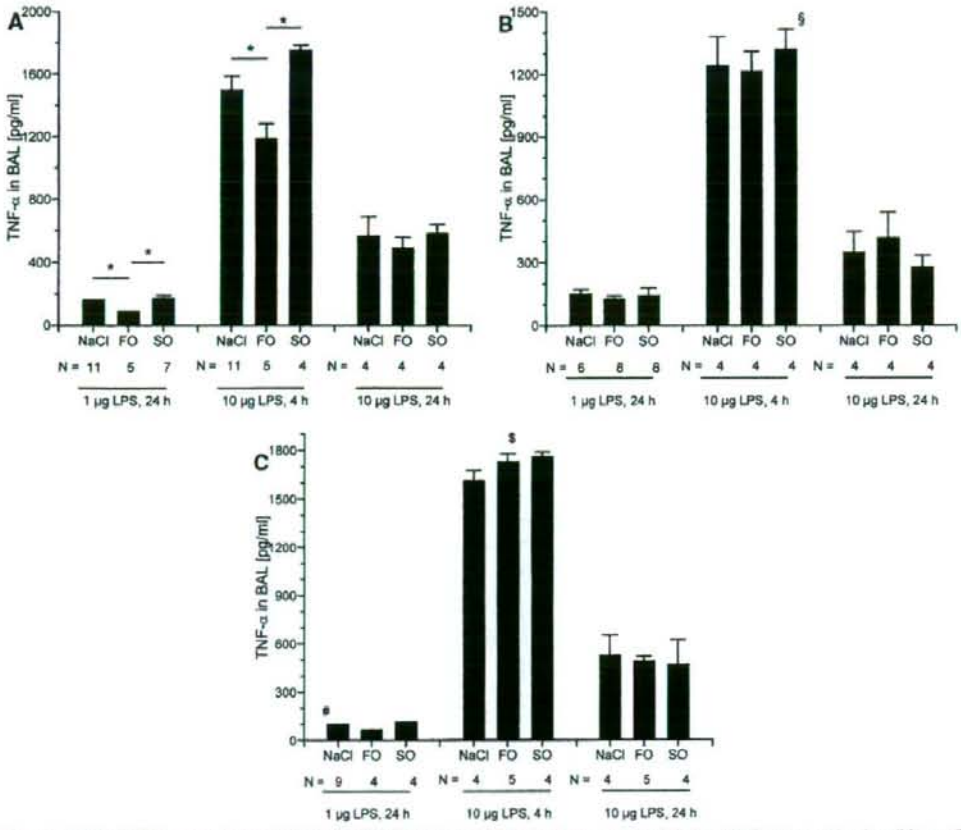

Figure 3. Impact of fish oil (*FO*)- vs. soybean oil (*SO*)-based lipid infusions on alveolar tumor necrosis factor (*TNF*)-α generation in wild-type (WT) mice, mice lacking the platelet-activating factor-receptor (PAF-R −/−), and WT mice treated with platelet-activating factor receptor antagonist (PAF-RA) in a model of acute lung injury. WT mice (*A*), PAF-R−/− mice (*B*), and WT mice treated with a PAF-RA (*C*) were infused for 3 days with saline (control) or FO- or SO-based lipid emulsions, followed by stimulation with 1 or 10 μg of endotoxin (lipopolysaccharide, LPS) intratracheally 4 or 24 hrs before lavage. TNF-α concentration in bronchoalveolar lavage was determined by enzyme-linked immunosorbent assay. Infusion of FO resulted in decreased TNF-α formation in WT mice (*$p < .05$ vs. SO and control). In PAF-R−/− mice or WT mice treated with PAF-RA, no significant impact of lipid emulsions could be detected. In PAF-RA mice challenged with 1 μg of LPS, TNF-α concentration of the NaCl group was lower compared with corresponding WT animals (#$p < .05$). After infusion of FO in PAF-RA mice, TNF-α concentration was higher compared with the WT-FO and PAF-R−/−-FO animals receiving 10 μg of LPS after 4 hrs ($$p < .05$). TNF-α concentration was lower in the PAF-R−/−-SO group after 10 μg of LPS and 4 hrs compared with the WT-SO and PAF-RA-SO animals ($$p < .05$). Data are given as mean ± SEM. Numbers of animals per group are detailed below columns. Error bars are missing when falling into symbol.

Before LPS challenge, we did not detect TNF-α in plasma in all groups. Following intraperitoneal LPS application, plasma TNF-α concentration rose to 303 ± 20 pg/mL in control animals. Infusion of SO-based lipids resulted in a significant increase of nearly 50% in TNF-α plasma concentration (Fig. 4*C*, $p < .01$ vs. control). After infusion of FO-derived lipids, TNF-α decreased significantly to 181 ± 12 pg/mL ($p < .05$ vs. control and $p < .001$ vs. SO). LPS challenge in PAF-R −/− mice infused with NaCl evoked a similar TNF-α concentration compared with WT controls (Fig. 4*D*). Again, no significant difference between the different infusion groups became detectable.

DISCUSSION

Using two different models of acute inflammation in mice, we have demonstrated that a 3-day course of lipid emulsion infusions is sufficient to modulate inflammatory responses induced by LPS. In contrast to SO-based lipid emulsions, FO-based lipid emulsions reduced pulmonary leukocyte invasion, protein leakage, and cytokine generation as well as cytokine appearance in the intravascular compartment. We present evidence that diverging effects of lipids emulsions are linked to PAF-R signaling. In mice carrying the disrupted PAF-R gene (PAF-R −/−), as well as in mice treated with a PAF-RA, the general response to endotoxin remained intact, but the differential response to FO vs. SO lipids was lost. A drawback of both models applied is the use of LPS in a single-hit model to induce inflammatory responses. Such a model is clearly different from clinical and experimental sepsis induced by bacterial infection.

Responses to endotoxin in PAF-R −/− mice were intact in our acute lung injury

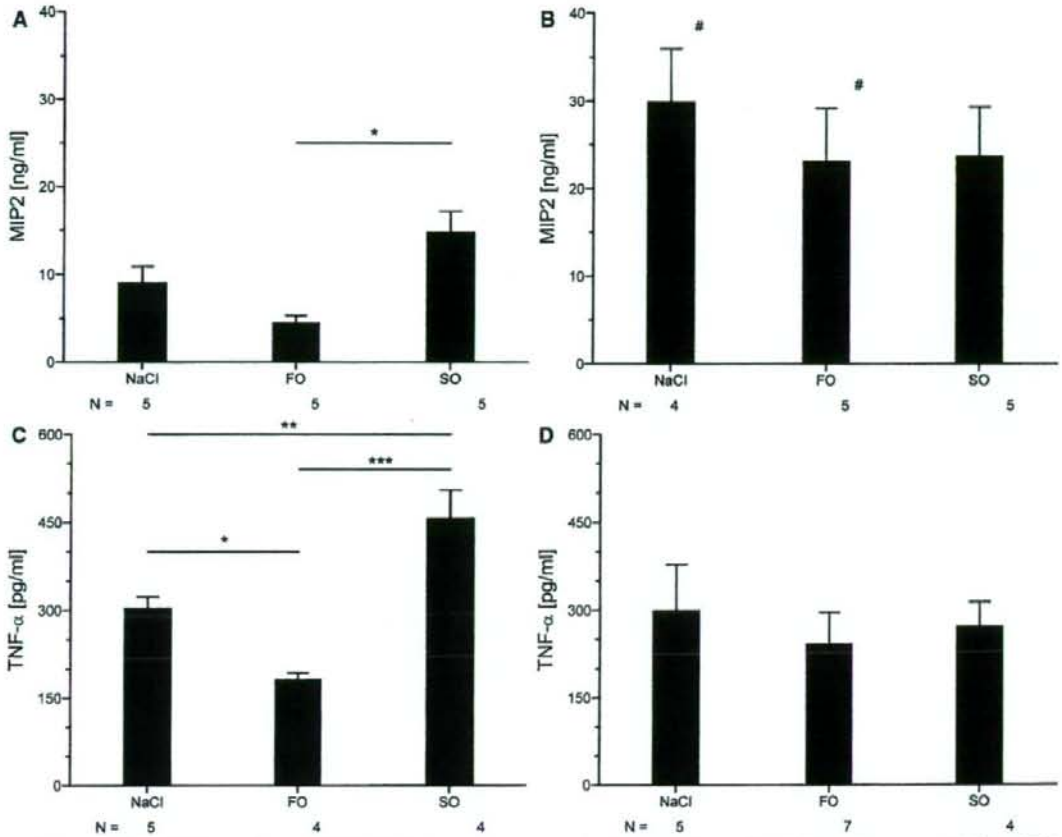

Figure 4. Impact of fish oil (*FO*) vs. soybean oil (*SO*) lipid infusions on plasma macrophage inflammatory protein (*MIP*)-2 and tumor necrosis factor (*TNF*)-α in wild-type (WT) mice and mice lacking the platelet-activating factor-receptor (PAF-R −/−) in a model of intraperitoneal inflammation. WT mice (*A, C*) or PAF-R−/− mice (*B, D*) were infused for 3 days with saline (control) or FO- or SO-based lipid emulsions, followed by stimulation with endotoxin (lipopolysaccharide, LPS) intraperitoneally 2 hrs before kill. MIP-2 (*A, B*) and TNF-α (*C, D*) in plasma were determined by enzyme-linked immunosorbent assay. Infusion of FO resulted in decreased MIP-2 formation in WT mice (*$p < .05$ vs. SO) but not in PAF-R−/− mice. TNF-α was increased after SO but decreased after FO compared with NaCl in WT mice receiving LPS (*$p < .05$; **$p < .01$; ***$p < .001$). MIP-2 was higher in PAF-R−/− mice after infusion with NaCl or FO compared with corresponding WT groups ($p < .01$). Data are given as mean ± SEM. Numbers of animals per group are detailed below columns.

model. These data are well in line with a previous report demonstrating regular responses of PAF-R −/− mice in an endotoxic shock model (15). Our data documenting elevated plasma levels of MIP-2 in PAF-R −/− mice compared with WT mice remain enigmatic. Elevated MIP-2 levels were observed both after lipid infusions and in saline controls. We speculate that this increase may be part of a long-term compensatory mechanism due to PAF-R deficiency, since PAF and MIP-2 may both act as chemoattractants. Further investigations are required to explain this phenomenon. In the PAF-RA group, the overall response to endotoxin remained intact. However, we found a delay in transmigration of leukocytes compared with WT mice: In mice receiving 10 μg of LPS, after 4 hrs leukocyte numbers were reduced but rose to an equal number of leukocytes after 24 hrs. Furthermore, we found a reduction of MIP2 and TNF-α in BAL in mice receiving 1 μg of LPS but not after 10 μg of endotoxin.

A striking finding of the present study was the differential impact of the FO vs. SO on cytokine generation provoked by endotoxin challenge in WT mice. In mice undergoing conventional SO-based lipid infusion, an augmentation of TNF-α and MIP-2 (the murine equivalent of interleukin-8) concentration in response to LPS challenge was observed irrespective of the model employed. In contrast, infusion of FO in WT mice resulted in reduced proinflammatory cytokine generation under all experimental conditions investigated. Although this is the first report of continuous lipid infusion in murine acute lung injury, our observations are consistent with previous findings demonstrating that TNF-α and interleukin-1 release was suppressed by dietary n-3 fatty acids in isolated murine splenocytes (25) and in isolated monocytes obtained from septic patients undergoing FO-based lipid infusions (18). Several days to weeks of oral FO supplementation are usually necessary to achieve such a change, whereas a

3-day infusion course sufficed to cause changes in cytokine synthesis in the present study and in patients receiving intravenous lipids (18). However using continuous enteral feeding, Gadek et al. (16) found a rapid increase in n-3 fatty acids in plasma phospholipids. We speculate that a key issue may be the continuous delivery of higher doses of FO to achieve fast changes. Preliminary data in our model suggest a rapid increase in n-3 fatty acids in plasma after infusion of FO and increase in n-6 polyunsaturated fatty acids in the SO group.

Pulmonary leukocyte recruitment was reduced in WT mice receiving FO-derived lipid emulsions. In contrast, SO-derived n-6 lipids increased leukocyte invasion and lung injury. We and others have described increased injury to lungs undergoing inflammatory stress due to n-6 lipids and, vice versa, an amelioration of damage by administration of n-3 lipids (26, 27). Mechanisms underlying this protective effect include, at least in part, the effect of FO on cytokine response described previously, generation of less potent lipid mediators as leukotriene B_5 instead of leukotriene B_4, formation of the less active vasoconstrictor thromboxane A_3 instead of thromboxane A_2, a reduction in platelet-activating factor synthesis, and reduced adhesion of leukocytes to endothelial cells (28–30). Transmigration of leukocytes through the endothelial-epithelial structures is a complex and tightly regulated process. The n-3 lipids interfere with this process at multiple stages, involving reduced presentation of endothelial adhesion molecules and reduced formation of platelet-activating factor by endothelial cells, which may then result in diminished activation of integrins on rolling leukocytes (28, 31). Furthermore, addition of arachidonic acid to endothelial cells increased thrombin-induced formation of PAF; in contrast, supplementation with n-3 fatty acids reduced its formation (28). As PAF generated by endothelial cells is not secreted to the supernatant but remains bound to the cell membrane, it may activate rolling leukocytes by binding to their PAF-R and initiate adhesion and transmigration (32). This mechanism may be at least in part responsible for the reduced rolling and adhesion of monocytes to endothelial cells after exposure to n-3 fatty acids and may translate in reduced transmigration of leukocytes (28).

Infusion of lipid emulsions bypasses physiologic uptake and processing of triglycerides by the gastrointestinal tract. Instead, infusion of synthetic lipid aggregates activates endothelial lipoprotein lipases, with translocation of the enzyme from its cellular binding sites into vascular compartment. Activation and translocation of this enzyme result in an increase in plasma free fatty acids due to avoidance of local cellular uptake mechanisms (33). The kinetics and duration of elevated plasma n-3 lipid levels thus exceed the corresponding alterations in response to conventional dietary FO uptake by orders of magnitude (34). Different availability of precursor fatty acids not only has an impact on subsequent generation of lipid mediators (e.g., substitution of leukotriene B_5 for B_4) but also reduces the generation of PAF due to incorporation into the phospholipid-precursor pool. In this respect, at least two lipid-dependent mechanisms may be relevant. First, enrichment of n-3 fatty acids in the PAF precursor pool may result in steric inhibition of phospholipase A_2 (32). Conversely, the increasing availability of arachidonic acid enhances generation of platelet-activating factor (28). Second, increasing n-3 fatty acids in phosphatidyl-inositol may impair the activation of leukocytes through reduction in intracellular second-messenger generation and activation of protein kinase C (7).

Recent experimental and clinical investigations suggest a strong link between the availability of free arachidonic acid, PAF, and lung injury. PAF and LPS promote lung injury and edema through sphingomyelinase-dependent formation of ceramide and activation of the cyclooxygenase pathway, which leads to the generation of arachidonic acid-derived prostanoids (35). Rapid infusion of conventional lipid emulsions in mechanically ventilated patients suffering from acute respiratory distress syndrome increased pulmonary shunt, notably linked to enhanced prostanoid generation resulting in a deterioration of the Pao_2/Fio_2 ratio (36). A second study in acute respiratory distress syndrome patients undergoing lipid infusions reported an increase in BAL PAF concentration and neutrophil counts paralleled by a deterioration in lung function, as measured by decreased Pao_2/Fio_2 (37). Despite these results and experimental use of PAF-RAs exhibiting beneficial properties in models of sepsis and acute lung injury (12, 38), phase III clinical studies using PAF-RAs or PAF-acetylhydrolase in septic patients have failed to show a difference in survival (13, 14). There may be a gap between experimental studies, when sepsis is initiated by a single LPS challenge with simultaneously started treatment, and clinical reality. Furthermore, as the response to LPS was intact in our model using PAF-R −/− mice, it remains to be determined if other inflammatory response systems may compensate for the inhibited PAF pathway.

However, the role of PAF in lipid infusion-related deterioration of lung function is underscored by our experiments using mice with a targeted disruption of the PAF receptor gene. Employing this strain, we were able to demonstrate that intratracheal LPS instillation provoked recruitment of leukocytes, as well as TNF-α and MIP-2 generation to the same extent as in WT mice, a phenomenon already described (15). Nevertheless, aggravation of lung inflammation by SO and its amelioration by FO-derived emulsions were essentially abolished in mice lacking this receptor. These results were confirmed in WT mice treated with a PAF-RA. Using BN52021, the differential impact of FO vs. SO on leukocyte recruitment and cytokine generation was also blocked. We conclude that major proinflammatory effects of conventional lipid emulsions and the ameliorating impact of FO-derived lipid emulsions on inflammation and pulmonary injury are linked to the integrity of PAF and PAF-R-related signaling in mice.

The correct timing and dosing of any pro- or anti-inflammatory drug in inflammation and sepsis are currently unsettled. N-3/n-6 ratios of 7.6:1 (FO) or 1:370 (safflower oil) have immune-suppressive features in a heart transplantation model (39), and application of SO (ratio 1:6.4) in septic patients increased the cytokine response (19). However, a ratio of 1:2 was shown to have only a minor impact on immunity in the heart transplantation model (39). Applying an n-3/n-6 ratio of 1:2 or 1:3 may therefore be a means to evade immune-modulating effects. Whereas FO in a hyperinflammatory state may be judged as an adjunct therapy, it may prove not to be beneficial in patients with already reduced immune response. Nevertheless, recent data from an observational study in 661 patients including 276 septic patients suggest that supplementation of parenteral nutrition with 0.1–0.2 g/kg/day FO had favorable effects on survival rate, infection rates, and length of stay in this subgroup (40). In addition, current studies using an enteral immune-modulating diet including n-3 fatty ac-

ids in patients with acute respiratory distress syndrome or sepsis show improvement in Pao_2/Fio_2 ratio, reduction in ventilation time, and even improvement in survival (16, 41, 42).

CONCLUSIONS

We demonstrated that infusion of FO-based lipid emulsions reduces LPS-induced proinflammatory cytokines, alveolar leukocyte transmigration, and protein leakage. In contrast, SO-based lipids lead to a further increase in the inflammatory response. However, the effect of lipid emulsions in murine inflammation is dependent on an intact PAF/PAF-R signaling. Administration of lipid emulsions not only may be regarded as a simple supply of calories but may also modulate the inflammatory response.

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