Modulation of Voltage-Dependent and Inward Rectifier Potassium Channels by 15-Epi-Lipoxin-A4 in Activated Murine Macrophages: Implications in Innate Immunity

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Potassium channels modulate macrophage physiology. Blockade of voltage-dependent potassium channels (K_v) by specific antagonists decreases macrophage cytokine production and inhibits proliferation. In the presence of aspirin, acetylated cyclooxygenase-2 loses the activity required to synthesize PGs but maintains the oxygenase activity to produce 15R-HETE from arachidonate. This intermediate product is transformed via 5-LOX into epimeric lipoxins, termed 15-epi-lipoxins (15-epi-lipoxin A_4 [e-LXA_4]). K_v have been proposed as anti-inflammatory targets. Therefore, we studied the effects of e-LXA_4 on signaling and on K_v and inward rectifier potassium channels (K_ir) in mice bone marrow–derived macrophages (BMDM). Electrophysiological recordings were performed in these cells by the whole-cell patch-clamp technique. Treatment of BMDM with e-LXA_4 inhibited LPS-dependent activation of NF-κB and IkB kinase β activity, protected against LPS activation–dependent apoptosis, and enhanced the accumulation of the Nrf-2 transcription factor. Moreover, treatment of LPS-stimulated BMDM with e-LXA_4 resulted in a rapid decrease of K_v currents, compatible with attenuation of the inflammatory response. Long-term treatment of LPS-stimulated BMDM with e-LXA_4 significantly reverted LPS effects on K_v and K_ir currents. Under these conditions, e-LXA_4 decreased the calcium influx versus that observed in LPS-stimulated BMDM. These effects were partially mediated via the lipoxin receptor (ALX), because they were significantly reverted by a selective ALX receptor antagonist. We provide evidence for a new mechanism by which e-LXA_4 contributes to inflammation resolution, consisting of the reversion of LPS effects on K_v and K_ir currents in macrophages. The Journal of Immunology, 2013, 191: 6136–6146.
potassium channels (Kv) 2.1 current, whereas alternative activation downregulates Kc current (5, 15, 16). Experimental evidence indicates that in macrophages, the major Kc is a heterotrimERIC Kc1.3/Kc1.5 channel (15, 16). Innate activation changes the stoichiometry of these channels, increasing the Kc1.3:Kc1.5 ratio, whereas alternative activation decreases it (15, 16). However, less is known regarding the role of these channels in the resolution phase. Lipoxins are endogenous eicosanoids released during the resolution phase of inflammation (17–21), and they might modulate Kc activity. The potent anti-inflammatory and proresolving actions of these lipids have been demonstrated in multiple animal models of human diseases (22, 23). Both native LXa4 and e-LXa4 (20) bind to and activate the ALX receptor and decrease polymorphonuclear cells infiltration in rodent models of acute peritonitis (24). The endogenous protective role of ALX mediating the biological actions of lipoxins has been demonstrated in mice overexpressing the human ALX in myeloid cells (25). A recent study in which vascular inflammation in wild-type and ALX−/− mice was compared demonstrates that ALX activation controls platelet/neutrophil aggregates to afford LXa4 synthesis, inhibiting vascular inflammation on reperfusion, at the time that aspirin can jumpstart this circuit by triggering e-LXa4 synthesis (26). In the present work, we have studied the effects of e-LXa4 on Kc and Kc currents, compatible with attenuation of the inflammatory response.

Materials and Methods

Chemicals

LPS was from Invivogen (San Diego, CA), and e-LXa4 was from Cayman Chemical (Ann Arbor, MI). e-LXa4 (55,6R,1SR-trihydroxy-7,9-trans-11-cis-eicosatetraenoic acid) was dissolved in ethanol and stored protected from light at −80°C to prevent oxidation. Aliquots of a volume and concentration desired for each experimental condition were prepared. Other reagents were from Sigma-Aldrich (St. Louis, MO), Roche (Basel, Switzerland), Invitrogen (Carlsbad, CA), or Merck (Darmstadt, Germany). Cytokines were from PeproTech (Rocky Hill, NJ). Commercial Abs were from Santa Cruz Biotechnology (Santa Cruz, CA), Cell Signaling Technology (Danvers, MA), Abcam (Cambridge, U.K.), and BD Biosciences (Minneapolis, MN), Sigma-Aldrich, Alomone (Jerusalem, Israel), or PeproTech. Serum reagents were from Sigma-Aldrich (St. Louis, MO), Roche (Basel, Switzerland), Invitrogen (Carlsbad, CA), or Merck (Darmstadt, Germany).

Cell culture and transfection

Kc1.5 was cloned into a modified pBK plasmid (gift from Dr. M.M. Tamkun, Colorado State University, Fort Collins, CO). Kc1.3 was cloned into pEFPP-C1 (gift from Dr. A. Felipe, Universidad de Barcelona, Barcelona, Spain), and Kc2.1 was cloned into pcDNA3.1 (gift from Dr. E. Delpón, Universidad Complutense de Madrid, Madrid, Spain). HEK293 cells were cultured in DMEM supplemented with 10% FBS and antibiotics (Sigma-Aldrich). Transfection of Kc1.5 (0.5 μg), Kc1.3 (0.2 μg), or Kc2.1 (0.5 μg) and CD8 reporter plasmid (1.6 μg) was performed by using FuGene-6 in a 1:3 ratio (μl/μg). Before experimental use, cells were incubated with polylysine microbeads precoated with anti-CD8 Ab (Dynabeads M450, Dynal), as previously described (27).

Treatment of animals and preparation of BMDM

BALB/c mice were housed and bred in our pathogen-free facility. Animal care and experimental procedures were performed according to the 2010/63/ EU Directive of the European Parliament and approved by the Institutional Committee on Bioethics (authorization 28079-37A to the Instituto de Investigaciones Biomédicas). Total bone marrow was obtained by flushing pelvises, femurs, and tibiae with DMEM. BMDM were prepared as follows: bone marrow mononuclear phagocytic precursor cells were propagated in suspension by culturing in DMEM containing 10% FBS, 100 U/ml penicillin, 100 μg/ml streptomycin, and 0.2 mM recombinant murine M-CSF (PeproTech) in tissue-culture plates. The precursor cells became adherent within 7 d of culture. For priming of BMDM, the cells were maintained in DMEM medium supplemented with 10% FBS for 14 h prior to use. Experiments were carried out in phenol-red free DMEM medium and 2% of heat-inactivated FBS plus antibiotics.

Flow cytometry

Cells were harvested and washed in cold PBS. After centrifugation at 4°C for 5 min and 1000 × g, cells were resuspended in Annexin V binding buffer (10 mM HEPES [pH 7.4], 140 mM NaCl, and 2.5 mM CaCl2). Cells were labeled with Annexin V–FITC (BD Pharmingen, San Jose, CA) and/or propidium iodide (PI; 100 μg/ml) for 15 min at room temperature in the dark. PI is impermeable to living and apoptotic cells but stains necrotic and apoptotic dying cells with impaired membrane integrity in contrast to Annexin V, which stains early apoptotic cells (28).

Determination of intracellular calcium concentration

Ca2+ concentration was measured in BMDM cells seeded at 50% subconfluence over coverslips (9 mm) and loaded with fura 2-AM (final concentration 5 μM) at 37°C for 30 min in serum-free medium containing 2 μg/ml pluronic to favor the dispersion of the probe. After loading, the cells were washed twice with PBS and kept in 1 mL phenol red–free RPMI 1640 medium containing 2 mg/ml fatty acid–free BSA. The fluorescence was recorded at 510 nm in an LS55B Perkin-Elmer spectrophotometer (Perkin-Elmer, Norwalk, CT) provided with continuous stirring and using a dual excitation source at 340 and 380 nm. The maximal and minimal fluorescence of the assay were determined for each sample after addition of 1% SDS and 5 mM EGTA (pH 9), respectively (29).

Preparation of cell extracts

BMDM cells (six-well dishes) were washed twice with ice-cold PBS and homogenized in 0.2 mL buffer A (10 mM Tris-HCl [pH 7.5], 1 mM MgCl2, 1 mM EGTA, 10% glycerol, 0.5% CHAPS, 1 mM 2-ME, 0.1 mM PMSF, and a protease and phosphatase inhibitor mixture Sigma–Aldrich). The extracts were vortexed for 30 min at 4°C and centrifuged for 15 min at 13,000 × g. The supernatants were stored at −20°C. Proteins levels were determined using the Bio-Rad detergent–compatible protein reagent (Bio-Rad, Richmond, CA). All steps were carried out at 4°C.

Western blot analysis

Samples of cell extracts containing equal amounts of protein (30 μg/lane) were boiled in 250 mM Tris-HCl (pH 6.8), 2% SDS, 10% glycerol, and 2% 2-ME and size-separated in 10–15% SDS-PAGE. The gels were blotted onto a polyvinylidene difluoride membrane (GE Healthcare) and processed as recommended by the supplier of the Abs against the murine Ags: NO synthase-2 (NOS-2; sc-7271), cyclooxygenase (COX)-2 (sc-1747), heme oxygenase-1 (HO-1; AB-1284; Millipore), Arg-1 (sc-20150), Arg-2 (sc-292), p65 (3034; Cell Signaling Technology), Nrf-2 (sc-13032), IκBα (sc-371), p-IκBα (2859;Cell Signaling Technology), p-IκB kinase (IKKb) (2681; Cell Signaling Technology), IKK (2678; Cell Signaling Technology), KcB (APC002), KcA (APC004), β-tubulin (sc-9935), and β-actin (A-5441). The blots were developed by ECL protocol (GE Healthcare), and different exposition times were performed for each blot with a charged coupling device camera in a luminescent image analyzer (Molecular Imager; Bio-Rad) to ensure the linearity of the band intensities.

Immunofluorescence of Kc and Kc proteins

Cells were seeded into sterile eight-well Chamber Slides (Falcon, Lincoln Park, NJ) and activated for the indicated times. After fixation for 10 min with 2% paraformaldehyde, cells were then permeabilized in iced methanol and incubated with 3% BSA for 30 min. After incubation with Abs against Kc or Kc at 4°C for 18 h, cells were washed with PBS followed by incubating with Alexa 488 anti-rabbit secondary Ab at 4°C for 1 h at room temperature (1:500; Molecular Probes) and Hoechst 33342. Coverslips were mounted in Vectorshield (Vector Laboratories, Burlingame, CA) and examined using an Espectral Leica TCS SP5 confocal microscope (Leica Microsystems). Fluorescence intensity was quantified using ImageJ software (National Institutes of Health, Bethesda, MD).

Measurement of IκKa activity

To determine the direct effect of e-LXa4 in vitro, IκKa activity was measured by homogeneous time-resolved fluorescence assay using cloned and expressed IκKa and biotinylated IκBα (aa 28–40) as substrate. Fluorescence (excitation at 330 nm and emission at 615 and 665 nm) was recorded after addition of europium cryptate p-Ab recognizing the S32/S36
phosphorylation peptide and streptavidin-XL665. Inhibition of IKKβ by staurosporine was used as control (30).

RNA isolation and RT-PCR analysis

A total of 1 μg total RNA, extracted with TRIzol Reagent (Invitrogen) according to the manufacturer’s instructions, was reverse transcribed using Transcriptor First Strand cDNA Synthesis Kit for RT-PCR following the indications of the manufacturer (Roche). Real-time PCR was conducted using specific TaqMan probes on a MyiQ Real-Time PCR System (Bio-Rad). PCR thermocycling parameters were 95°C for 10 min, 40 cycles of 95°C for 15 s, and 60°C for 1 min (31). All samples were analyzed for 36B4 expression in parallel as housekeeping control. Each sample was run in duplicate and normalized to 36B4.

Electrophysiological recordings

Whole-cell currents were measured using the patch clamp technique with an Axopatch 200B amplifier (Axon Instruments) and stored on a personal computer with an analog-to-digital converter DigiData 1400A (Axon Instruments). pClamp version 9 software (Axon Instruments) was used for data acquisition and analysis. Currents were recorded at 21–23°C and stimulation frequency of 0.1 Hz and sampled at 4 kHz after anti-alias filtering at 2 kHz. Patch electrodes of 2–4 MΩ were fabricated in a P-87 puller (Sutter Instruments) from borosilicate glass capillary tubes (GD-1; Narishige). Gigahm seal formation was achieved by suction (2–5 GΩ; n = 60). After seal formation, cells were lifted from the bath, and the membrane patch was ruptured with a brief additional suction. The capacitive transients elicited by symmetrical 5-mV steps from −80 mV were recorded at 50 kHz and filtered at 10 kHz for subsequent calculations of capacitative surface area, access resistance, and input impedance. Thereafter, capacitance and series resistance compensation were optimized, and, usually, 80% compensation of the effective access resistance was obtained. Electrodes were filled with an intracellular pipette solution containing (mM): K-aspartate 80, KCl 50, phosphocreatine 3, KH2PO4 10, MgATP 3, HEPES-K 10, and EGTA-K 5 and was adjusted to pH 7.25 with KOH. The bath solution contained (mM): NaCl 130, KCl 4, CaCl2 1.8, MgCl2 1, HEPES 10, and glucose 10 and was adjusted to pH 7.4 with NaOH. Uncompensated series resistances were 4–8 MΩ. As currents evoked were <1 nA, voltage errors from uncompensated series resistance were <2 mV. Inactivation was fit to an exponential process using an equation of the form: \[ y = A \exp(-v/\tau) + C, \] where \( \tau \) is the system time constant, \( A \) is the amplitude, and \( C \) is the baseline value.

Statistics

Data are expressed as the mean ± SEM. The significance of differences was established by Student’s t test or Pearson product-moment correlation coefficient with a two-tailed p value (Prism 4.0; GraphPad) when indicated. The curve-fitting procedure used a nonlinear least-squares (Gauss-Newton) algorithm; results were displayed in linear format. Goodness of fit was judged by the \( \chi^2 \) criterion and by inspection for systematic nonrandom trends in the difference plot. A p value < 0.05 was considered significant.

Results

Macrophage profiling upon activation

BMDM were challenged with LPS or IL-4/IL-13, and the expression of genes characteristics of the LPS (NOS-2, COX-2, and IP-10: M1 (A), D, E) or the mean ± SEM of three experiments. \(* p < 0.05, ** p < 0.01\) versus the control condition (in the absence of stimuli), \( p < 0.05 \) versus values obtained in LPS-activated BMDM cells. CTRL, Control.

FIGURE 1. Macrophage profiling after stimulation through the innate and alternative pathways and effect of e-LXA4 on activation. BMDM were maintained in culture and activated for the indicated period with LPS (100 ng/ml) or IL-4/IL-13 (20 ng/ml each). The expression of proteins characteristics of each pathway (A) was determined by Western blot. The extent of apoptosis/necrosis under these conditions was determined by the staining with Annexin V and PI, respectively (B). Cells were treated with e-LXA4 (200 nM) for 30 min prior the challenge with LPS (100 ng/ml), and the effect of e-LXA4 on apoptosis/necrosis in LPS-activated BMDM was determined (C). The activation of IKK (D) and the presence of p65 and Nrf-2 in the nuclei of BMDM (E) were determined at 0–120 min. The effect of e-LXA4 (200 nM) on the protein levels of NOS-2, COX-2, HO-1, Arg-1, and Arg-2 were determined at 10–30 h (F). Band intensities were normalized for content in β-actin (D, F) or β-tubulin (E), and the ratios p-IKK/IKK and p-IkBα/IkBα (D), and the p65, Nrf-2 (E), NOS-2, COX-2, and HO-1 levels (F) were represented as percentage over the maximal value in each ratio or lane. e-LXA4 inhibited IKKβ activity in homogeneous time-resolved fluorescence in vitro assays, using staurosporine (Stauron) as control inhibitor (G). Results show a representative experiment out of four (A, D–F) or the mean ± SEM of three experiments. \(* p < 0.05, ** p < 0.01, *** p < 0.001\) versus the control condition (in the absence of stimuli). \( p < 0.05 \) versus values obtained in LPS-activated BMDM cells. CTRL, Control.
markers) and IL-4/IL-13 activation (HO-1 and Arg-1: M2 markers) confirmed the differential phenotype of these populations upon treatment (Fig. 1A). Approximately 20% of LPS-activated M1 macrophages exhibited apoptosis, whereas IL-4/IL-13-activated M2 macrophages did not (Fig. 1B). In agreement with previous data (22) and in part due to the attenuation of the LPS-dependent activation, treatment of BMDM with e-LXA₄ protected against apoptosis (Fig. 1C). Treatment of BMDM with e-LXA₄ significantly impaired IKK activation and IkBα phosphorylation and subsequent degradation in response to LPS stimulation (Fig. 1D), an effect that was further evidenced by the decreased translocation of p65 to the nucleus and the enhanced accumulation of Nrf-2, a transcription factor activated in response to e-LXA₄ (Fig. 1E). In agreement with this anti-inflammatory pattern (22), a decrease in the expression of NOS-2 and COX-2 and a moderate expression of HO-1 (an Nrf2-dependent gene) at 10 h after e-LXA₄/LPS challenge was observed (Fig. 1F). In addition to these effects, e-LXA₄ exhibited a moderate but significant direct inhibition of IKKβ when analyzed in vitro, using staurosporine as a control inhibitor (Fig. 1G).

**Early effects of e-LXA₄ on Kv₆ of BMDM**

Voltage-dependent potassium currents were evoked in BMDM by applying depolarizing pulses from a holding potential of −80 mV to different voltages from −80 to 60 mV in 10-mV steps. Fig. 2 shows original records of Kv₆ currents obtained in control (resting) or activated with LPS or IL-4/IL-13 BMDM (Fig. 2A–C), before and after perfusion (15 min) with e-LXA₄. Fig. 2D–F shows the current-voltage relationships (I-V) obtained in the absence and in the presence of e-LXA₄. Resting and IL-4/IL-13–stimulated BMDM elicited small Kv₆ currents of similar magnitude that were not modified by perfusion with e-LXA₄. However, LPS-stimulated BMDM elicited inactivating Kv₆ currents of greater amplitude. Perfusion with e-LXA₄ significantly decreased Kv₆ currents at potentials >0 mV (20 ± 3% at +60 mV; n = 12, p < 0.05) (Fig. 2E). Because it has been described that the increase of Kv₆ current induced by LPS is due to an upregulation of Kv₁.3 (5), this early inhibition of Kv₆ current produced by e-LXA₄ could be due, at least in part, to its effects on Kv₁.3. Use-dependent inactivation of certain K⁺ channels, a unique property of Kv₁.3 but not of Kv₁.5, is characterized by an inactivation that accumulates after repetitive depolarizing pulses because recovery during the interpulse interval is incomplete (16, 32). Supplemental Fig. 1A–C shows the use-dependency of Kv₆ currents in control BMDM or activated with LPS or IL-4/IL-13 before and after perfusion with e-LXA₄, as well as the graphs in which the normalized current was plotted against the number of the pulse during the train. The magnitude of use-dependent inactivation observed in control BMDM was small, 15 ± 5% (n = 10), but increased to 69 ± 3% (n = 10; p < 0.01 versus control) in LPS-activated BMDM. In contrast, stimulation with IL-4/IL-13 led to a marked decrease of the use-dependent inactivation (1.6 ± 3%; n = 8, p < 0.01 versus control). Perfusion with e-LXA₄ was unable to modify the degree of use-dependent decrease of the current. As shown in Supplemental Fig. 1D–F, Kv₆ currents are inactivated with a different time course in control versus LPS or IL-4/IL-13–challenged BMDM. Cumulative and use-dependent are useful parameters to evaluate differences in the nature of the tetrameric K⁺ channel phenotype, because Kv₁.3 present cumulative and use-dependent inactivation, which is absent in Kv₁.5 (16, 33). Supplemental Fig. 1D–F shows the time course of Kv₆ current inactivation after applying a depolarizing pulse from −80 to +60 mV for 1 s. Although Kv₆ currents are inactivated with a time constant of 1899 ± 1275 ms (n = 5) in control BMDM, this parameter decreased to 456 ± 43 ms in LPS-treated cells (n = 10; p < 0.05 vs. control). However, this process was slower in BMDM activated with IL-4/IL-13 (10,591 ± 5,826 ms; n = 7, p < 0.05 versus control) (Supplemental Fig. 1F). These results further support the notion that Kv₆ currents generated upon depolarization in BMDM are mediated by Kv₆ channels with different subunit stoichiometry after activation with LPS or with IL-4/IL-13 (5, 16).

**FIGURE 2.** Early effects of e-LXA₄ on Kv₆ currents. Representative traces of Kv₆ currents recorded in control, LPS-, and IL-4/IL-13–activated BMDM (top panel). Cells were untreated (A) or treated with LPS (100 ng/ml) (B) and IL-4/IL-13 (20 ng/ml) (C) for 18 h. Current recordings were obtained in the absence and after perfusion during 15 min with e-LXA₄ (500 nM) (A–C). Currents were elicited by applying depolarizing pulses from a holding potential of −80 mV to different depolarizing voltages from −80 to +60 mV in 10-mV steps (250-ms duration). I-V relationships in the absence and presence of e-LXA₄ (500 nM) in nonstimulated BMDM (D), LPS (E), and IL-4/IL-13–activated BMDM (F) are shown. *p < 0.05 versus control; n > 10 cells/group. CTRL, Control.
Kir currents were evoked by applying pulses from a holding potential of \(-80\) mV to different voltages from \(-140\) to \(+40\) mV in 10-mV steps (Supplemental Fig. 2A–C). Resting and IL-4/IL-13–activated BMDM showed similar magnitudes of the Kir currents; however, cells activated with LPS elicited Kir currents of smaller amplitude. The mean I-V relationship for Kir currents and the degree of Kir inactivation are shown in Supplemental Fig. 2. In all experimental conditions, e-LXA4 decreased the current at negative potentials to \(-120\) mV (12 ± 4\%, \(n = 10\); 18 ± 9\%, \(n = 12\); and 23 ± 4\%, \(n = 7\)) at \(-140\) mV in resting, LPS, and IL-4/IL-13–stimulated BMDM, respectively. The decrease of the current magnitude induced by e-LXA4 was accompanied, in resting and LPS-stimulated BMDM, by a higher degree of inactivation of the current.

**Chronic effects of e-LXA4 on Kv and Kir of BMDM**

Because e-LXA4 produces changes in gene expression in addition to early signaling, the long-term effects of e-LXA4 were analyzed on Kv and Kir currents. The effects of 18-h treatment with e-LXA4 in resting or LPS-stimulated BMDM are shown in Fig. 3. The effects of e-LXA4 on IL-4/IL-13–stimulated BMDM were not shown.

**FIGURE 3.** Effect of long-term treatment with e-LXA4 on Kv currents in control and LPS-activated BMDM. Representative traces of Kv currents recorded in control (resting) and LPS-activated BMDM. BMDM were incubated with e-LXA4 (500 nM) (A), with LPS (100 ng/ml), or with e-LXA4 + LPS for 18 h (B). Currents were elicited by applying depolarizing pulses from a holding potential of \(-80\) mV to different depolarizing voltages from \(-80\) to \(+60\) mV in 10-mV steps (250-ms duration). I-V relationships obtained in control BMDM and after incubation for 18 h with e-LXA4 (C). I-V relationships obtained in LPS stimulated BMDM and after incubation with e-LXA4 + LPS during 18 h (D). To measure Kv inactivation, the pulse protocol shown in the middle panel of the figure was applied and representative traces of Kv currents recorded in control or e-LXA4 (500 nM) (E) and in LPS-activated or incubated with e-LXA4 (500 nM) + LPS (100 ng/ml) BMDM (F). Plots show the normalized current measured at the maximum peak current during the application of a train of depolarizing pulses. Current records obtained after applying a depolarizing pulse of 1 s in control cells or incubated with e-LXA4 (G) and in LPS-activated or incubated with e-LXA4 BMDM (H). Note that incubation with e-LXA4 reverts the LPS-induced effects on use-dependent and kinetics of inactivation. *\(p < 0.05\) versus control; \(n > 10\) cells/group. CTRL, Control.
studied due to the slight changes produced by IL-4/IL-13 on Kᵣ and Kᵢᵣ currents. Treatment of BMDM with e-LXA₄ (18 h) did not change the Kᵣ outward current versus that elicited in resting BMDM at any membrane potential tested (Fig. 3C). However, the combined stimulation of BMDM with e-LXA₄ + LPS significantly decreased Kᵣ current at membrane potentials > −10 mV, reverting the magnitude current values toward those observed in resting cells (546 ± 152 versus 178 ± 48 pA measured at the end of +60 mV pulses; n = 7–9, p < 0.05; Fig. 3D).

As shown in Supplemental Fig. 1, one of the characteristics of the Kᵣ currents recorded in LPS-activated BMDM is the use-dependent inactivation observed upon application of a train of stimuli. Fig. 3E and 3F show the long-term effects induced by e-LXA₄ (18 h) on the use-dependent inactivation of the Kᵣ currents in resting and LPS-stimulated BMDM. e-LXA₄ did not modify the degree of use-dependent inactivation in resting BMDM (Fig. 3E), as shown in the graphs representing the normalized peak Kᵣ current during the application of train pulses. Interestingly, Kᵣ generated by BMDM activated by e-LXA₄ + LPS did not exhibit the use-dependent inactivation characteristic of Kᵣ,1.3 (Fig. 3F).

Similarly, incubation with e-LXA₄ did not modify the inactivation kinetics of resting BMDM, whereas it slowed this process in LPS-stimulated cells (1123 ± 335 versus 456 ± 43 ms in cells incubated with e-LXA₄ + LPS and LPS, respectively, n = 6–11, p < 0.05; Fig. 3G, 3H). These results suggest that e-LXA₄ prevents the LPS-induced changes in the stoichiometry of Kᵣ, leading to the formation of heterotetramers with a lower Kᵣ,1.3:Kᵣ,1.5 ratio. Thus, the resulting Kᵣ phenotype closely resembles that of resting BMDM.

Kᵣ currents were recorded in BMDM by using the same pulse protocol described in Supplemental Fig. 2 and are shown in the top panel of Fig. 4. Similarly to that observed in Kᵣ currents, e-LXA₄ did not modify Kᵣ current magnitude versus resting BMDM (Fig. 4A, 4C). However, in LPS-activated BMDM, e-LXA₄ reverted LPS effects, increasing the Kᵣ current magnitude at membrane potentials < −90 mV (Fig. 4B, 4D). Interestingly, in all the experiments in which cells were incubated with e-LXA₄ + LPS, e-LXA₄ returned the current biophysical characteristics toward the control situation (Fig. 3A). These results could be explained either by e-LXA₄–induced changes in the expression of both Kᵣ and Kᵢᵣ or by posttranslational channel protein modifications. To address this question, the mRNA and protein levels were measured. Our data show an upregulation of the Kᵣ,1.3 mRNA by LPS that was impaired when cells were pretreated with e-LXA₄ (Fig. 5A). e-LXA₄ promoted a modest upregulation of Kᵣ,1.5 mRNA that was suppressed by LPS or IL-4/IL-13. Kᵣ,2.1 mRNA levels were downregulated by LPS, and to a lesser extent by IL-4/IL-13. Interestingly, when the protein levels were determined at 18 h (the time of evaluation of the biochemical and electrophysiological parameters), a significant increase of Kᵣ,1.3 and Kᵣ,2.1 protein levels was observed after LPS challenge, an effect that was blunted by e-LXA₄ (Fig. 5B). The mRNA and protein level changes of Kᵣ,1.3 and Kᵣ,1.5 were in agreement with the electrophysiological results shown above. Moreover, the mRNA levels of Kᵣ,2.1 observed after BMDM incubation with LPS were in agreement with the reduced Kᵣ,2.1 recorded under these experimental conditions. However, there are controversial results for the mRNA and protein levels of Kᵣ,2.1 after incubation with e-LXA₄, e-LXA₄ + LPS, or IL-4/IL-13. Moreover, the increase in the protein levels of Kᵣ,2.1 does not correlate with the electrophysiological results observed, which could be attributed to posttranslational modifications as evidenced by the appearance of two adjacent protein bands in LPS-activated cells. Representative confocal microscopy images of the distribution of the fluorescence of Kᵣ,2.1 show areas of aggregation, perhaps in specific intracellular environments (Fig. 5C).

![FIGURE 4](http://www.jimmunol.org/) Long-term e-LXA₄ (500 nM) effects on Kᵣ currents recorded in nonstimulated and LPS-activated BMDM. Representative traces of Kᵣ currents recorded in control and LPS-activated BMDM. BMDM were not stimulated (A, top panel) or activated with LPS (100 ng/ml) (B, top panel) for 18 h. We also show records obtained from control cells pretreated with e-LXA₄ (A, bottom panel) or e-LXA₄ + LPS (B, bottom panel). Currents were elicited by applying hyper- and depolarizing pulses from a holding potential of −80 mV to different depolarizing voltages from −140 to −40 mV in 10-mV steps (500-ms duration). I-V relationships obtained in nonstimulated BMDM and after incubation with e-LXA₄ (500 nM) during 18 h (C). I-V relationships obtained in LPS-stimulated BMDM and after incubation with e-LXA₄ + LPS during 18 h (D). Current recordings were obtained in the absence and after perfusion with e-LXA₄ (500 nM). *p < 0.05 versus control; n > 10 cells/group. CTRL, Control.

To assess whether e-LXA₄ produces its effects via a direct interaction with the ion channels or through changes in the LPS signaling pathway, two series of experiments were performed. First, we analyzed the effects of different e-LXA₄ concentrations (1–1000 nM range) on cloned Kᵣ,1.5, Kᵣ,1.3, and Kᵣ,2.1 expressed in HEK293 cells (Supplemental Fig. 3A). As it can be observed, e-LXA₄ did not produce significant effects on any ion channel, suggesting that the effects observed in the current study are not due to a direct interaction between e-LXA₄ and the channels. In the second approach, the effects of low concentrations of e-LXA₄ were analyzed in Kᵣ, and Kᵣ in LPS-stimulated BMDM cells (Supplemental Fig. 3B, 3C). e-LXA₄ reverted in a concentration-dependent manner the effects of LPS both on Kᵣ and Kᵣ currents with IC₅₀ of ∼250 and ∼120 nM, respectively.

Another important issue to be assessed is the relative potency of e-LXA₄ versus LXA₄. To analyze this issue, we studied the long-term effects of LXA₄ 500 nM in Kᵣ and Kᵣ currents recorded in LPS-stimulated BMDM cells. As it can be observed, e-LXA₄ did not produce significant effects on any ion channel, suggesting that the effects observed in the current study are not due to a direct interaction between e-LXA₄ and the channels. In the second approach, the effects of low concentrations of e-LXA₄ were analyzed in Kᵣ, and Kᵣ in LPS-stimulated BMDM cells (Supplemental Fig. 3B, 3C). e-LXA₄ reverted in a concentration-dependent manner the effects of LPS both on Kᵣ and Kᵣ currents with IC₅₀ of ∼250 and ∼120 nM, respectively.

To gain insight on the mechanism of action of e-LXA₄ in BMDM cells the effects on the endoplasmic reticulum release of Ca²⁺ and on the influx via calcium release–activated calcium channels (CRAC) were analyzed. Treatment of BMDM with thapsigargin induced a transient increase in the intracellular Ca²⁺ concentration.
due to Ca\(^{2+}\) efflux from intracellular stores. Subsequent addition of Ca\(^{2+}\) (1 mM) to the extracellular medium produced a further increase in intracellular Ca\(^{2+}\) concentration indicative of store- 
opened Ca\(^{2+}\) entry. Supplemental Fig. 4A shows the effects produced by e-LXA\(_4\) in resting and LPS-stimulated 
BMDM on Ca\(^{2+}\) release and Ca\(^{2+}\) influx. Under all experimental conditions, Ca\(^{2+}\) release from intracellular stores 
was similar. When analyzing the Ca\(^{2+}\) influx mainly via CRAC, e-LXA\(_4\) did not produce significant changes in the 
fluorescence under resting conditions. The increase in fluorescence was greater in LPS-stimulated BMDM (\(p < 0.01\)), and, interestingly, e-LXA\(_4\) significantly decreased fluorescence values in LPS-stimulated BMDM (\(p < 0.01\)), an effect 
that was affected after treatment with margatoxin (MgTx; \(p < 0.01\)) (see below; Supplemental Fig. 4A).

Blockade of Kv1.3 with MgTx prevents the e-LXA\(_4\) effects

To know whether the e-LXA\(_4\) effects on the Kv and Kir are critical 
for its immunomodulatory activity on LPS-stimulated BMDM 
cells, a series of experiments in the presence of MgTx (10 nM), a 
selective Kv1.3 blocker, was performed. We observed that, in the 
presence of MgTx, the effects of e-LXA\(_4\) on NOS-2, IP-10, and 
Arg-1 were suppressed (Fig. 6A, 6B), suggesting that Kv1.3 ac-
tivity is required for the action of this eicosanoid. Moreover, the 
impairing effects of e-LXA\(_4\) on LPS-triggered IKK signaling were 
also antagonized by MgTx (Fig. 6C).

e-LXA\(_4\) produces its effects partially via ALX receptor

The biological effects of e-LXA\(_4\) have been shown to be mediated, at least in part, via ALX receptor (34, 35). Using a selective 
ALX inhibitor (BocPLP; 1 \(\mu M\)) (36, 37), >85% inhibition of the 
e-LXA\(_4\)-dependent ERK phosphorylation was observed [data 
not shown and (22)]. Fig. 7 shows the effects of BocPLP on Kv1.3 
and Kv1.5 currents and the I-V relationships in different combi-
nations of LPS and e-LXA\(_4\) treatments of BMDM. The actions 
of e-LXA\(_4\) on Kv and Kir appear to be partially mediated via 
ALX receptor. The biophysical characteristics of Kv currents 
were very similar to those recorded in cells activated with LPS 
and to a lesser extent with LPS + e-LXA\(_4\). However, as shown 
in the Kv I-V relationship (Fig. 7A), the mean magnitude of 
the current resulted to be smaller than that recorded in cells 
activated with LPS and somewhat greater than that obtained 
after stimulating with e-LXA\(_4\) + LPS (Fig. 7A). Kv currents still 
exhibit cumulative inactivation as occurred in LPS-stimulated 
cells in the absence of e-LXA\(_4\) (Fig. 7B). Under this line, the 
Kv inactivation recorded in BMDM stimulated with e-LXA\(_4\) + 
LPS in the presence of BocPLP was intermediate between that 
observed in LPS- and in e-LXA\(_4\) + LPS–stimulated cells (Fig. 
7C), suggesting that the effects of e-LXA\(_4\) on Kv currents are 
partially ALX receptor dependent. Regarding the effects of BocPLP 
on the Kv current in BMDM treated with e-LXA\(_4\) + LPS, the inward 
current was similar to that recorded in LPS-activated BMDM,
suggesting that Kir effects are more ALX receptor dependent than those on Kv currents.

Because the anti-inflammatory actions of e-LXA₄ have been also observed at very low concentrations, the effects of 100 nM e-LXA₄ were analyzed on Kv and Kir currents recorded in BMDM activated with LPS (Supplemental Fig. 4B–E). The effects of 100 nM e-LXA₄ on the magnitude of Kv currents were smaller than those induced by 500 nM e-LXA₄, and pretreatment with 100 nM e-LXA₄ did not abolish the use-dependent inactivation, as did 500 nM e-LXA₄ (Supplemental Fig. 4B–E). Moreover, the time course of inactivation was very similar to that observed in BMDM activated with LPS (Supplemental Fig. 4D). Regarding the action of e-LXA₄ (100 nM) on Kir, this low concentration partially reverted the effects induced by LPS, but to a lesser extent than did 500 nM e-LXA₄ (Supplemental Fig. 4E).

**Discussion**

This study provides experimental evidence for a new mechanism of action of e-LXA₄ by which this eicosanoid contributes to inflammation resolution: on the one hand by directly attenuating NF-κB activity and on the other hand affecting the electrophysiological properties of the macrophage membrane. We show that: 1) activation of BMDM with IL-4/IL-13 produces similar effects on potassium currents than those reported after glucocorticoid treatment; 2) following perfusion, e-LXA₄ decreases Kv currents in LPS-elicited BMDM and also Kir currents in resting, LPS-, and IL-4/IL-13-stimulated BMDM at potentials negative to −120 mV, suggesting the involvement of receptor-independent effects; 3) after prolonged incubation of BMDM with e-LXA₄, the LPS-induced effects on Kv, and Kir were partially reverted, at the time that the enhanced levels of Kv1.3 and Kir2.1 were downregulated; 4) long-term...
agonist (BocPLP). Kv currents were slightly reverted versus those recorded in LPS-activated BMDM pretreated with e-LXA4 (A). Similar effects were observed on the use-dependent inactivation (B) and time course of inactivation observed after applying 1-s depolarizing pulses (C). Kv currents were reverted versus K_o currents recorded in LPS-activated BMDM pretreated with e-LXA4 (D). Note that the effects of e-LXA4 on K_o were slightly receptor dependent, whereas those produced on K_v current are highly receptor dependent. n > 10 cells/group. CTRL, Control.

FIGURE 7. e-LXA4 produces its effects partially via interaction with ALX. Effects of pretreatment with e-LXA4 on K_v currents recorded in LPS-activated BMDM in the presence of an ALX antagonist (BocPLP). K_v currents were slightly reverted versus those recorded in LPS-activated BMDM pretreated with e-LXA4. A). Similar effects were observed on the use-dependent inactivation (B) and time course of inactivation observed after applying 1-s depolarizing pulses (C). K_v currents were reverted versus K_o currents recorded in LPS-activated BMDM pretreated with e-LXA4 (D). Note that the effects of e-LXA4 on K_o were slightly receptor dependent, whereas those produced on K_v current are highly receptor dependent. n > 10 cells/group. CTRL, Control.

Potassium channels play a critical role in maintaining the electrochemical gradient required for sustained Ca^{2+} entry in the time frame necessary for activation and effector functions (38). We previously reported that LPS-activated RAW 264.7 macrophages exhibited a 1.6-fold elevation in functional K_v versus the nonstimulated counterparts (16). Also, we described that K_v,1.3 and K_v,1.5 heteromeric channel expression and their biophysical and pharmacological properties changed differentially upon activation and immunosuppression: LPS induced K_v,1.3, whereas treatment with dexamethasone resulted in the opposite effect (16). This enhanced K_v,1.3 expression is likely to promote the Ca^{2+} signaling necessary for coactivation/effector functions in macrophages. Indeed, blockade of K_v,1.3 suppresses Ag-driven proliferation and cytokine production in T cells, and selective K_v,1.3 blockers ameliorate experimental allergic encephalomyelitis in rats induced by the adoptive transfer of myelin-specific activated effector memory T cells (39–42). Moreover, several groups have reported the expression of K_v,1.3 in macrophages and microglia (5, 16, 43–48), and our data add new insights on the fine-tuning of these channels by lipoxins. Indeed, K_v,1.3 channels, together with K_v,2.1, K_v,1.5, K_ca,3.1, and BKCa channels, modulate macrophage and microglia function, and, at the same time, pharmacological channel blockers may have effects on the immune response (5, 44, 49, 50).

Early effects of e-LXA4 on K_v and K_o

The effects of e-LXA4 were analyzed in nonactivated (resting) and innate or alternatively activated BMDM. In resting cells, the outward K_v current shows small amplitude, a fast activation, and a slow inactivation. Under these conditions, e-LXA4 did not produce significant effects on the biophysical properties of BMDM. Moreover, most of the K_v current is due to the activity of K_v,1.5 + K_v,1.3 tetramers in which K_v,1.5 predominates (5, 16). These results suggest that e-LXA4 does not produce significant direct effects on K_v,1.5 channels, and experiments performed on K_v,1.5 confirmed these results (see Supplemental Material).

As previously reported, LPS increases K_v and decreases K_o currents (5, 15, 16). The increase in K_v,1.3 current induced by LPS appeared concomitantly with a use-dependent decay and a C-type inactivation, both characteristics of K_v,1.3. Moreover, LPS up-regulated both the mRNA and protein levels of K_v,1.3. Under these conditions, e-LXA4 decreased the magnitude of the K_v current in LPS-stimulated BMDM but did not modify the use-dependent decrease or the C-type inactivation of the current. Although these effects point out to a direct interaction with K_v,1.3, the analysis of the response to e-LXA4 in HEK293 cells expressing these channels rules out this hypothesis, suggesting that the e-LXA4 actions are the consequence of some effect on a signaling pathway present in macrophages but not in HEK293 cells. Finally, after stimulation of BMDM with IL-4/IL-13, K_v currents exhibited similar magnitudes to those recorded in resting cells. Interestingly, although activation of BMDM with IL-4/IL-13 did not modify the amplitude of the current, it decreased the use-dependent effects, resembling the actions of dexamethasone (16). These results suggest that alternative activation can change the stoichiometry of K_v, leading to the formation of channels with a decreased K_v,1.3:K_v,1.5 ratio. These conclusions are supported by the slight increase in the mRNA levels for K_v,1.5 after IL-4/IL-13 activation. In BMDM stimulated with IL-4/IL-13, e-LXA4 did not produce significant effects on the magnitude nor on the electrophysiological properties of K_o currents.

In resting and alternatively activated BMDM, K_o current exhibits the typical characteristics of the inward rectifying potassium current. e-LXA4 decreased the amplitude of the K_o,2.1 current at negative membrane potentials under the three experimental conditions tested. In resting BMDM, but not in LPS- or IL-4/IL-13-stimulated BMDM, the reversal potential became more positive, which leads to a depolarization of the membrane potential, thus avoiding Ca^{2+} entry into the cell. As it was previously reported, LPS decreased K_o current, consistent with a downregulation in the mRNA for K_o,2.1 (5).
Long-term effects of e-LXA4 on Kᵥ and Kᵦv.

Because the early inhibitory effects of e-LXA4 on NF-κB and proinflammatory signaling are extended at later periods (>10 h), the electrophysiological effects of long-term incubation with e-LXA4 were studied at these times. Under these conditions, e-LXA4 did not modify the magnitude of the Kᵥ or the Kᵦv currents in resting BMDM. On the contrary, it was able to revert partially the electrophysiological effects produced by LPS, decreasing the amplitude, the use-dependent decrease, and the C-type inactivation of the Kᵥ current. In a parallel way, e-LXA4 increased the magnitude of the Kᵦv current previously decreased by LPS. Using a selective inhibitor of ALX (22), it was shown that the actions of e-LXA4 on Kᵥ currents are, at least in part, dependent on the interaction with ALX receptor. Indeed, the Kᵥ,1.5 protein levels were not regulated by e-LXA4, whereas Kᵥ,1.3 was upregulated by LPS and downregulated by e-LXA4 in LPS-stimulated BMDM. Because Kᵥ currents recorded in BMDM stimulated with LPS are the consequence of the activation of heteromultimers of Kᵥ,1.5 + Kᵥ,1.3 with different stoichiometry, the contribution of Kᵥ,1.5 to the total of this current can explain the apparently low dependency of the effects of e-LXA4 on Kᵥ. On the contrary, the Kᵦv current measured in the presence of BocPLP in cells treated with e-LXA4 + LPS was similar to that recorded in BMDM activated with LPS, suggesting that the e-LXA4 effects on Kᵦv involves the interaction with the ALX receptor.

The influx of extracellular Ca²⁺ is an essential requirement for the activity of many cellular processes (6, 51, 52). Therefore, Kᵥ,1.3 and the Ca²⁺-activated K⁺ channel KCa3.1 regulate Ca²⁺ influx through the Ca²⁺ release-activated Ca²⁺ channel, which consists of the Ca²⁺-sensor stromal interaction molecule 1 and the pore-forming protein CRACM1 (Orai1) (53–56). In T cells, this crucial influx of Ca²⁺ is only possible if they can keep their membrane potential negative by a counterbalance of K⁺ efflux through Kv1.3 and/or KCa3.1 (38, 57), and both channels are regarded as targets for immunosuppression (38). In the current study, we demonstrated that e-LXA4 inhibits Kᵥ,1.3 in LPS-stimulated cells. This inhibition should lead to a depolarization of the membrane potential and therefore to an inhibition of the Ca²⁺ influx through CRAC, which is a crucial event in the activation of macrophages (58). Indeed, we demonstrated that e-LXA4 is able to decrease extracellu-

lary influx of Ca²⁺ (Supplemental Fig. 4A). Therefore, e-LXA4 may produce anti-inflammatory effects through this new mechanism of action.

In conclusion, lipoxins were the first mediators exhibiting both anti-inflammatory and proresolving actions. The beneficial actions of aspirin in the cardiovascular system have been attributed to the capability of aspirin to block PG and prothrombotic thromboxane generation via acetylation of COX. Aspirin acetylation of COX-2 not only inhibits prostandoin formation but also alters the active site of COX-2 and thereby favors the conversion of arachidonic acid into 15R–HETE in vascular endothelial cells. This compound can be further transformed to epimeric lipoxins by leukocytes and other immune cells contributing to the fine tuning of the inflammatory response. Our data describe a direct inhibition of e-LXA4 on IKKβ activity, a broad inhibition on NF-kB activity, and a cytotoxic mechanism of macrophages during resolution. Also, the function of Kᵥ,1.3 channels are required for the attenuation of NF-kB activity, because the e-LXA4 effects on IKK activity and NFkB-2 expression are partially reverted by MgTx. Finally, and in addition to this, Ca²⁺ fluxes are negatively modulated by e-LXA4 through the inhibition of Kᵥ,1.3 channels in LPS-stimulated cells; all these mechanisms converging in the attenuation of the inflammatory response as far as e-LXA4 accumulates in the medium.
MODULATION OF Kg AND K13 CHANNELS BY e-LXA4


