Lipopolysaccharide-induced down-regulation of Ca2+ release-activated Ca2+ currents (ICRAC) but not Ca2+-activated TRPM4-like currents (ICAN) in cultured mouse microglial cells

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Lipopolysaccharide-induced down-regulation of Ca\(^{2+}\) release-activated Ca\(^{2+}\) currents (I\(_{\text{CRAC}}\)) but not Ca\(^{2+}\)-activated TRPM4-like currents (I\(_{\text{CAN}}\)) in cultured mouse microglial cells

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Microglia are the main immunocompetent cells of the mammalian central nervous system (CNS). Activation of cultured microglial cells and subsequent release of nitric oxide and cytokines critically depends on intracellular calcium levels. Since microglia undergo dramatic morphological, biochemical and electrophysiological changes in response to pathological events in the CNS, we investigated temporal changes in expression levels of ion channels involved in cellular calcium homeostasis in mouse cortical microglial cells in culture. Specifically, we assessed the inward and delayed outward rectifier potassium currents (I\(_{\text{IRK}}\) and I\(_{\text{DRK}}\)), calcium (Ca\(^{2+}\)) release-activated Ca\(^{2+}\) currents (I\(_{\text{CRAC}}\)) and Ca\(^{2+}\)-activated TRPM4-like currents (I\(_{\text{CAN}}\)) in non-activated microglia and cells that were activated by exposure to lipopolysaccharide (LPS) between 3 and 48 h. Unstimulated microglial cells, subcultured from an astrocyte coculture, typically exhibited a ramified, rod-shaped morphology. During the first 3 days of culture cell size and shape were maintained, but the percentage of cells showing prominent I\(_{\text{IRK}}\) went up and those expressing I\(_{\text{DRK}}\) went down. Cells retaining I\(_{\text{DRK}}\) exhibited smaller amplitudes, whereas those of I\(_{\text{IRK}}\) and I\(_{\text{CRAC}}\) were not affected. However, after 24 h of exposure to 1 \(\mu\)g ml\(^{-1}\) LPS, most cells showed an amoeboid (‘fried egg’-shaped) morphology with a 62% increase in cell capacitance. At that point in time, only 14% of the cells revealed I\(_{\text{IRK}}\) and 3% had I\(_{\text{DRK}}\) exclusively, whereas the majority of cells expressed both currents. The amplitudes of I\(_{\text{CRAC}}\) and I\(_{\text{IRK}}\) progressively decreased after stimulation, whereas I\(_{\text{DRK}}\) transiently reached a maximum after 6 h of LPS exposure and then returned to pre-stimulation expression levels. Cultured microglia also revealed TRPM4-like, Ca\(^{2+}\)-activated non-selective currents (I\(_{\text{CAN}}\)) with an EC\(_{50}\) of 1.2 \(\mu\)M [Ca\(^{2+}\)]. The expression levels of this current did not change significantly during and after 24 h of LPS exposure. We propose that LPS-induced down-regulation of I\(_{\text{IRK}}\) and I\(_{\text{CRAC}}\) will reduce the cell’s capacity to produce significant calcium influx upon receptor activation and result in decreased sensitivity to exogenous stimulation. In this scenario, I\(_{\text{CAN}}\) expression would remain constant, although its activity would automatically be reduced due to the diminished calcium influx capacity of the cell.

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Microglia derive from cells of the monocytic lineage entering the brain from the bloodstream during early embryonic development. They differentiate into brain resident cells and become the main immune effector cells in the CNS. Microglia are recognized for their scavenging function in response to pathological events (McGeer et al. 1988; Dickson et al. 1991; Bo et al. 1994; McGeer & McGeer, 1995; Meda et al. 1995; Baker & Manuelidis, 2003; Streit et al. 2004; Jack et al. 2005; Sargsyan et al. 2005; Conde & Streit, 2006; Wang et al. 2007).

Microglia appear in three different shapes as ramified, amoeboid and intermediate cells (del Rio Horta, 1932; Kershbaum, 1939) and three different physiological states as resting, activated and amoeboid-phagocytic cells (Streit et al. 1989; Sasaki et al. 1993). Ramified microglia, representing 5–20% of all glia in the normal
CNS (Lawson et al. 1990), is often referred to as resting microglia, since they respond to insults such as infection, traumatic injury or ischaemia by converting into amoeboid macrophage-like cells that move towards the site of injury (Thomas, 1992; Vilhardt, 2005). Following activation, microglia change their shape and express a distinct pattern of ion channels linked to their activation state (Norenberg et al. 1994; Biro et al. 1998; Farber & Kettenmann, 2005). Cultured microglia mainly express voltage-independent inward and, depending on the state of activation, voltage-gated outward potassium currents (Norenberg et al. 1992, 1994; Pyo et al. 1997; Eder, 1998; Walz & Bekar, 2001). However, microglia of freshly isolated rat cortical brain slices reveal little, if any, inward potassium or voltage-gated membrane currents (Boucsein et al. 2000). Thus, cultured microglial cells might not represent the fully resting state of microglia in vivo, although they remain responsive to a variety of stimuli that induce further changes in microglial properties.

The by far most frequently used model stimulus to study microglia activation and inflammatory signalling is the Gram-negative bacterial cell-wall component lipopolysaccharide (LPS). LPS activates the microglial Toll-like receptor-4 (TLR-4) and induces the transcription of genes that are involved in initiation or regulation of the inflammatory response (Hoshino et al. 1999; Lee & Lee, 2002). As a result, microglial cells change their shape (abd-el Basset & Fedoroff, 1995; Kloss et al. 2001), express various secretory compounds such as cytokines/chemokines, growth factors, tumour necrosis factor-α (TNF-α), super-oxide, nitric-oxide (NO) and prostaglandin E2 (PGE2) (Nakamura et al. 1999; Ajmone-Cat et al. 2003; Rock et al. 2004), and show increased expression levels of glutamate transporter 1 (GLT-1) (Persson et al. 2005). They develop inward rectifying potassium currents (I_{IRK}) in vivo (cultured microglias already show I_{IRK}, see above and present study) and voltage-gated, delayed rectifying potassium currents (I_{DRK}) carried by Kv1.3 and/or Kv1.5 channels in culture and Kv1.5 in vivo (Kettenmann et al. 1990; Norenberg et al. 1992, 1994; Pyo et al. 1997; Jou et al. 1998; Boucsein et al. 2000). LPS also induces calcium (Ca^{2+}) transients in cultured microglial cells, possibly resulting from caffeine-sensitive Ca^{2+} release (Bader et al. 1994) and/or dependent on Ca^{2+} influx (Herms et al. 1997; Choi et al. 2002; Yi et al. 2005). A permanent elevation of the basal Ca^{2+} concentration along with a suppression of UTP-evoked Ca^{2+} signalling has also been described for LPS-exposed cultured microglial cells (Hoffmann et al. 2003).

A recent model, first established in Jurkat T cells, proposes that several ion channels act in concert to shape calcium signals in immune cells (Launay et al. 2004). Here, TRPM4, a Ca^{2+}-activated non-selective (CAN) channel and Ca^{2+} release-activated Ca^{2+} currents (I_{CRAC}), as well as Kv1.3 and K_{Ca} control intracellular Ca^{2+} oscillations through oscillatory changes in membrane potential (Launay et al. 2004). Since LPS-induced chronic elevation of intracellular Ca^{2+} attenuates receptor-induced Ca^{2+} signals in activated microglia cells (Hoffmann et al. 2003), we wondered whether this would be achieved by an LPS-induced change not only in I_{IRK} or I_{DRK}, but also I_{CRAC} and CAN channels, if the latter were expressed in cultured microglial cells. Since most studies have only assessed endpoint states of microglia activation, we also wanted to learn about the kinetics of ion channel expression, particularly with respect to early effects (< 24 h) of LPS.

We therefore set out to first confirm the presence of Ca^{2+}-activated TRPM4-like currents in microglial cells. We then established a temporal profile of morphological and electrophysiological changes in cultured cortical mouse microglial cells over a period of 7 days in subculture and early responses to continuous exposure to 1 μg ml^{-1} LPS as a model of microglial cell activation. We used the patch-clamp technique to investigate LPS-dependent changes of inward and delayed outward rectifier potassium currents (I_{IRK} and I_{DRK}), Ca^{2+} release-activated Ca^{2+} currents (I_{CRAC}) and Ca^{2+}-activated TRPM4-like currents (I_{CAN}) in non-activated and LPS-stimulated cultured mouse microglial cells.

**Methods**

**Preparation and culture of mouse microglial cells**

Microglial cells were obtained from cortex of mouse pups (postnatal days 0–2) as previously described (Giulian & Baker, 1986). In brief, pups were decapitated in accordance with the University of Hawaii Institutional Animal Care and Use Committee guidelines after anaesthesia with enflurane (5–10 drops onto tissue in 200 ml beaker), and their brains were collected under sterile conditions in basal Eagle’s medium (BME, Gibco). Cortices were dissected, the meninges removed, and triturated after enzymatic digestion with 0.25% trypsin/5.26 mM EGTA and washing in glial medium (BME supplemented with 1% L-glutamine and 2 ml^{-1} penicillin–streptomycin). The homogenate was then forced through a 20 nm filter and the resulting suspension was plated in 75 cm^{3} poly l-lysine-coated glass coverslips in glial medium with 10% fetal bovine serum (FBS). The cells were kept in an incubator at 37°C and 5% CO_{2}, and the medium was changed 3 days following preparation and once per week thereafter. After about 3–4 weeks in culture, the flask showed a confluent layer of astrocytes with microglial cells growing on its surface. Microglial cells were harvested and isolated by shaking the flask to release the loosely attached microglia into the supernatant. Microglia from the supernatant were washed and plated on poly l-lysine-coated glass coverslips in glial medium with 5% FBS. Plated cells were used for patch clamp experiments 1–7 days after harvest. To
allow the cells to adapt to the subculture conditions, LPS experiments started 3 days after harvest. For microglia activation, 1 μg ml⁻¹ lipopolysaccharide (LPS) was added to the media 3–48 h before starting patch-clamp experiments.

Salines

All salines were freshly prepared from refrigerated stock solutions. The external saline to measure inward and delayed outward rectifying potassium currents (I_{IRK}, I_{DRK}) was composed of (mm): NaCl 140, KCl 10, CaCl₂ 1, MgCl₂ 2, glucose 10, HEPES-NaOH 10, pH 7.2. The external solution for TRPM4-like currents contained 2.8 mm KCl and for I_{CRAC} recordings, 2.8 mm KCl and 10 mm CaCl₂. Intracellular pipette-filling solutions for I_{IRK} and I_{DRK} contained (mm): potassium glutamate 140, NaCl 8, MgCl₂ 1, HEPES-KOH 10, pH 7.2; for I_{CRAC} (mm): caesium glutamate 140, NaCl 8, MgCl₂ 1, Cs-BAPTA 10, InsP₃ 0.02, HEPES-CsOH, pH 7.2.

Patch-clamp experiments

Coverslips with subcultured microglial cells were transferred to a recording chamber and kept in the modified Ringer solution described above. Patch pipettes were prepared from borosilicate glass capillaries (inner diameter 1.5 mm, Kimble products) using a horizontal puller (Sutter Instruments, Modell P-97), fire-polished, and had resistances between 2 and 4 MΩ. Patch-clamp experiments were performed in the tight-seal whole-cell configuration at room temperature (22–24°C). High-resolution current recordings were acquired by a computer-based patch-clamp amplifier system (EPC-9, HEKA). For I_{CRAC} recordings, voltage ramps of 50 ms duration spanning a voltage range of −130 to 100 mV over 50 ms were delivered from a holding potential \( V_h \) of 0 mV every 2 s over a period of 200 s. For I_{IRK} and I_{DRK} measurements, ramps from −130 to 100 mV were applied with \( V_h = −60 \) mV. Calcium-activated (TRPM4-like) currents were measured using ramps from −100 to −100 mV at a \( V_h \) of 0 mV and for 350 s. All voltages were corrected by a 10 mV liquid junction potential. Currents were filtered at 2.9 kHz and digitized at 100 μs intervals. Capacitive currents and series resistance were determined and corrected before each voltage ramp using the automatic capacitance compensation of the EPC-9. In I_{CRAC} experiments, the first one to three ramps were subtracted from all following ramps to subtract background conductances. The low-resolution temporal development of currents at a given potential was extracted from individual ramp current recordings by measuring the current amplitudes at voltages of −110 mV for I_{IRK} and I_{CRAC}, +80 mV for I_{DRK} and −80 mV and +80 mV for TRPM4-like currents. All currents were normalized to cell size to obtain current densities (pA pF⁻¹).

Fura-2 Ca²⁺ measurements

For Ca²⁺ measurements, cells were loaded with 1 μM Fura-2 AM (acetoxyxymelester, Molecular Probes) for 60 min in media at 37°C, washed and kept in external solution containing (mm): NaCl 140, KCl 2.8, CaCl₂ 1, MgCl₂ 2, glucose 10, HEPES-NaOH 10, pH 7.2. The Ca²⁺-dependent Fura-2 fluorescence of several cells was monitored at a rate of 0.2 Hz with a dual excitation fluorometric imaging system (TILL-Photonics, Gräfelfingen, Germany) controlled by TILLvisION software, using a Zeiss Axiovert 100 fluorescence microscope equipped with a 40× Plan-NeoFluar objective. Fura-2 AM-loaded cells were excited by wavelengths of 340 and 380 nm and the fluorescence emission, detected at 450–550 nm, was computed into relative ratio units (F₃₄₀/F₃₈₀).

Statistics

Where applicable, statistical errors of averaged data are given as means ± s.e.m. with \( n \) determinations and statistical significance assessed by Student’s \( t \) test.

Results

Properties of non-activated and LPS-exposed mouse microglia

In acutely isolated brain slices, resting microglia are initially highly ramified and transform to amoeboid-like morphology within several hours (Stence et al. 2001). Here we studied shape and size of microglial cells harvested and replated from a primary coculture with astrocytes. The subcultured microglia exhibited either a ramified, rod-shaped appearance or a ‘fried egg’-shaped morphology (Fig. 1A, left and right, respectively). Some of the cells showed a more round intermediate morphology, but with clear ramification (Fig. 1A, middle) and were therefore classified as ramified cells. From day 1 to day 7 after subculturing, about 90% of the cells represented the ramified and 10% the ‘fried-egg’-shaped type (Fig. 1B). The cell membrane capacitance, which is proportional to cell surface area, was on average 12 ± 0.6 pF \((n = 76)\) at day 1 and did not change significantly during the first 4 days. Thereafter the cell capacitance increased to 18.1 ± 1 pF \((n = 38)\) at day 6 and 17.5 ± 1 pF \((n = 35)\) at...
day 7 (Fig. 1D). After adding 1 μg ml⁻¹ lipopolysaccharide (LPS), a widely used activator of microglial cells, 34% of the cells revealed a ‘fried egg’-shaped morphology already within 3 h. Within 48 h, the ratio of cell types completely reversed to just 6% ramified and 94% ‘fried egg’-shaped cells (see Fig. 1C). The cell size increased to 23 ± 0.6 pF (n = 155) after 24 h and to 43.9 ± 2.6 pF (n = 43) after 48 h of incubation with LPS (Fig. 1E). Since LPS experiments were performed later than 3 days after harvest, control cells not exposed to LPS (Fig. 1C and E) represent the average data from day 3 to day 7. Bath application of 1 μg ml⁻¹ LPS induced a prolonged Ca²⁺ signal (Fig. 1F) that set in after a marked delay of 40–50 min. After 3 h, intracellular Ca²⁺ concentration reached basic levels again, but further decreased significantly and reached a minimum after 12 h before settling in to values slightly higher than before LPS application (Fig. 1G).

**LPS-dependent down- and up-regulation of I_{IRK} and I_{DRK}**

The delayed outward rectifier (DRK) and inward rectifier (IRK) potassium channels are the dominant and best-studied ion channels in cultured microglial cells. Their down- and up-regulation often is used as a marker for the microglial activation status (Norenberg et al. 1994; Eder, 1998; Walz & Bekar, 2001). We determined the changes of inward and outward potassium currents of subcultured microglia over a period of 1–7 days after harvest and 3–48 h after incubation and activation with 1 μg ml⁻¹ LPS. On the first day after harvest, 2.8 ± 2.8% of the cells revealed expression of I_{IRK} only, 26.1 ± 5.7% expressed I_{DRK} only, and a majority of 71.1 ± 7.4% showed both types of potassium currents (n = 4 coverslips with 36 cells; Fig. 2A). Figure 2C–E shows sample current–voltage (I–V) relationships of microglial cells.

**Figure 1.** Morphology, cell size and [Ca²⁺]i

A, composite image of scanning electron micrographs of microglial cells at various stages of activation with 1 μg ml⁻¹ LPS from non-activated (left cell, arborized) to fully activated (right cell, ‘fried egg’-shaped). B and C, percentage of ramified (●, ± s.e.m.) and ‘fried egg’-shaped (○, ± s.e.m.) cells per coverslip depending on time in subculture (B, day 1 n = 12, 2 n = 10, 3 n = 9, 4 n = 5, 5 n = 5, 6 n = 8, 7 n = 5 coverslips, 2142 cells) and incubation time in 1 μg ml⁻¹ LPS (C, 0 h n = 32, 3 h n = 6, 6 h n = 8, 12 h n = 4, 24 h n = 9, 48 h n = 8 coverslips, 2211 cells). D and E, cell capacitance (in pf, ± s.e.m.) of microglial cells depending on time in subculture (D, day 1 n = 76, 2 n = 63, 3 n = 110, 4 n = 117, 5 n = 35, 6 n = 38, 7 n = 35 cells) and incubation time in 1 μg ml⁻¹ LPS (E, 0 h n = 335, 3 h n = 40, 6 h n = 49, 12 h n = 29, 24 h n = 155, 48 h n = 43 cells). The controls (0 h LPS) in C and E represent the average data from day 3 to day 7 in B and D, respectively. F and G, intracellular Ca²⁺ changes (F₄₃₀/F₃₈₀) during the first 3 h (F, n = 22, 2 coverslips) and basic internal Ca²⁺ up to 48 h (G) after incubation with 1 μg ml⁻¹ LPS. (G, 0 h n = 47, 3 h n = 57, 6 h n = 78, 12 h n = 54, 24 h n = 26, 48 h n = 45).
cells expressing \( I_{\text{IRK}} \) only (Fig. 2C), \( I_{\text{DRK}} \) only (Fig. 2D), or both \( I_{\text{IRK}} \) plus \( I_{\text{DRK}} \) (Fig. 2E). During the first 4 days in culture, the percentage of cells showing \( I_{\text{IRK}} \) only increased dramatically to 58.2 ± 15.2% (\( n = 4 \) coverslips with 32 cells) at the expense of cells expressing \( I_{\text{DRK}} \) or \( I_{\text{IRK}} + I_{\text{DRK}} \) (41.8 ± 15.2%). These relative proportions remained stable even after 7 days (\( n = 3 \) coverslips with 19 cells; Fig. 2A). With respect to average current amplitudes, \( I_{\text{DRK}} \) strongly decreased from 25.9 ± 3.4 pA pF\(^{-1} \) (\( n = 36 \)) at day 1 to 5.2 ± 0.9 pA pF\(^{-1} \) (\( n = 18 \)) at day 7, whereas \( I_{\text{IRK}} \) increased from 15.5 ± 2.2 pA pF\(^{-1} \) (\( n = 36 \)) at day 1 to 27.7 ± 4.1 pA pF\(^{-1} \) (\( n = 18 \)) at day 7 (Fig. 2F).

Since the most dramatic changes in potassium currents took place from day 1 to day 3, further experiments investigating early effects of LPS induction were performed on microglial cells at least 3 days in subculture. For these experiments, the unstimulated control data in Fig. 2B and G represent the average of data from day 3 to day 7. Within just 3 h, exposure of cells to 1 \( \mu \)g ml\(^{-1} \) LPS dramatically changed the ratio between cells expressing \( I_{\text{IRK}} \) only, \( I_{\text{DRK}} \) only and \( I_{\text{IRK}} + I_{\text{DRK}} \) (see Fig. 2B). After 6 h of LPS exposure, the number of cells revealing \( I_{\text{IRK}} + I_{\text{DRK}} \) more than doubled to 87.5 ± 5.1%, cells showing \( I_{\text{DRK}} \) increased about 4-fold to 12.5 ± 5.1% and at the same time, none of the cells expressed \( I_{\text{IRK}} \) (\( n = 4 \) coverslips with 28 cells; Fig. 2B).

However, within 48 h of LPS exposure the percentage of cells expressing \( I_{\text{IRK}} \) only recovered to 30.3 ± 15.1%, cells presenting \( I_{\text{IRK}} + I_{\text{DRK}} \) to 66 ± 13% and cells with \( I_{\text{DRK}} \) only to 3.7 ± 3.7% (\( n = 3 \) coverslips with 28 cells; Fig. 2B).

Acute LPS exposure not only affected potassium channel expression levels, but also their current amplitudes. \( I_{\text{DRK}} \) significantly increased and reached its peak after 6 h of exposure to 1 \( \mu \)g ml\(^{-1} \) LPS (43.9 ± 5.8 pA pF\(^{-1} \), \( n = 27 \)), before leveling off to control values again after 24 h of LPS exposure (10 ± 2.3 pA pF\(^{-1} \), \( n = 28 \); Fig. 2G). In contrast, the current size of \( I_{\text{IRK}} \) gradually decreased from control levels of 22.2 ± 1.5 pA pF\(^{-1} \) (\( n = 123 \)) to 5.6 ± 0.6 pA pF\(^{-1} \) (\( n = 28 \)) after 24 h of incubation with LPS (Fig. 2G).

**LPS-dependent down-regulation of \( I_{\text{CRAC}} \)**

\( Ca^{2+} \) release from intracellular stores plays a critical role in intracellular signalling in many cell types. In non-excitable cells, depletion of stores activates store-operated (capacitative) \( Ca^{2+} \) entry (SOCE) to induce cellular responses and refill the \( Ca^{2+} \) stores (Putney, 1986). The calcium release-activated calcium current (\( I_{\text{CRAC}} \)) (Hoth & Penner, 1992) is the best-characterized SOCE current and the main \( Ca^{2+} \) influx pathway in immunocompetent cells such as T-lymphocytes and mast

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**Figure 2. \( I_{\text{IRK}} \) and \( I_{\text{DRK}} \)**

A and B, percentage of microglial cells in culture showing just \( I_{\text{IRK}} \) (\( ± \) S.E.M.), just \( I_{\text{DRK}} \) (\( ± \) S.E.M.) or \( I_{\text{IRK}} + I_{\text{DRK}} \) (\( ± \) S.E.M.) depending on time in subculture (A, day 1 \( n = 4 \), 2 \( n = 3 \), 3 \( n = 4 \), 4 \( n = 4 \), 5 \( n = 2 \) 6 \( n = 3 \), 7 \( n = 3 \) coverslips, 183 cells) and incubation time in 1 \( \mu \)g ml\(^{-1} \) LPS (B, 0 h \( n = 16 \), 3 h \( n = 4 \), 6 h \( n = 12 \), 24 h \( n = 4 \), 48 h \( n = 3 \) coverslips, 274 cells). C, D and E, typical current–voltage relationships (I–V) of whole-cell currents in microglial cells revealing just \( I_{\text{IRK}} \) (C), just \( I_{\text{DRK}} \) (D) and both, \( I_{\text{IRK}} + I_{\text{DRK}} \) (E). F and G, average inward \( (I_{\text{IRK}}, ± \) S.E.M.) and outward \( (DRK, ± \) S.E.M.) currents (in pA pF\(^{-1} \)) measured at −110 and +80 mV, respectively, of microglial cells depending on time in subculture (F, day 1 \( n = 36 \), 2 \( n = 22 \), 3 \( n = 37 \), 4 \( n = 32 \), 5 \( n = 17 \), 6 \( n = 19 \), 7 \( n = 18 \) cells) and (G) incubation time in 1 \( \mu \)g ml\(^{-1} \) LPS (circles, 0 h \( n = 123 \), 3 h \( n = 18 \), 6 h \( n = 27 \), 12 h \( n = 15 \), 24 h \( n = 28 \), 48 h \( n = 25 \) cells). The controls (0 h LPS) in B and G represent the average data from day 3 to day 7 in A and F, respectively.
cells, but little is known about CRAC in microglial cells. We measured IP₃-induced CRAC currents in non-stimulated microglial cells over 1–7 days in subculture and during a period of 3–48 h of exposure to 1 μg ml⁻¹ LPS. Figure 3A shows the average development of I₉₃ over time, normalized to cell capacitance, in microglia from day 1, 3 and 6 after replating and subculturing. The normalized amplitude of CRAC currents, measured at its plateau phase after 150–200 s into the experiment, ranged between 1.2 ± 0.13 pA pF⁻¹ (n = 11, day 2) to 1.29 ± 0.08 pA pF⁻¹ (n = 12, day 4), and did not change significantly during the 7 days in subculture (Fig. 3A and B). However, after exposure to 1 μg ml⁻¹ LPS, current sizes of I₉₃ decreased with time of incubation from a control level (mean amplitude of I₉₃ from day 3 to day 7) of 1.25 ± 0.04 pA pF⁻¹ (n = 60, set as 100%) to about 58% (0.73 ± 0.11 pA pF⁻¹, n = 7) within 12 h and further to 41% (0.51 ± 0.06 pA pF⁻¹, n = 11) after 48 h of exposure (Fig. 3C and D). Figure 3E shows the typical inward rectifying average I–V relationships of leak-subtracted CRAC currents after 100 s into the experiment from unstimulated control cells and cells exposed to LPS (1 μg ml⁻¹) for 24 h and 48 h.

**Microglia express Ca²⁺-activated TRPM4-like currents**

Ca²⁺-activated non-selective cation channels, like the melastatin-related transient receptor potential channels TRPM4 and TRPM5, are widely expressed and proposed to be involved in membrane depolarization (Launay et al. 2002; Prawitt et al. 2003; Guinamard et al. 2004). In the present study we show that perfusing microglial cells with increasing intracellular Ca²⁺ concentrations through the patch pipette, recruits a TRPM4-like current in non-activated as well as LPS-induced (24 h exposure) cells in a dose-dependent manner (see Fig. 4A and C). The dose–response curve calculated for the inward current at −80 mV yields an EC₅₀ of 1.2 μM Ca²⁺ for control and 1.3 μM Ca²⁺ for 24 h LPS-exposed microglial cells (Fig. 4C). As seen with TRPM4 (Cheng et al. 2007), the Ca²⁺-activated current in microglia (Fig. 4A) developed in parallel with an increase in cell
capacitance (Fig. 4B), indicating that a proportion of channels might be recruited to the plasma membrane through exocytosis. The dose–response for inward and outward (data not shown) currents did not show any significant difference between non-activated and 24 h LPS-exposed microglial cells. However, 1.7 μM intracellular Ca\(^{2+}\) induced a faster recruitment of the TRPM4-like current in 24 h LPS-activated cells (see Fig. 4A). In addition, higher concentrations of Ca\(^{2+}\) (see Fig. 4A and 40 μM) resulted in a slightly larger outward current in non-activated (618 ± 55 pA pF\(^{-1}\), n = 19) compared with 24 h LPS-exposed microglia (520 ± 96 pA pF\(^{-1}\), n = 7). As the inward current revealed the same amplitude for control (375 ± 52 pA pF\(^{-1}\), n = 19) and LPS-activated cells (377 ± 68 pA pF\(^{-1}\), n = 7; see Fig. 4A and C) this results in a slightly stronger outward rectification of the TRPM4-like current in non-activated microglial cells. Figure 4D shows the average I–V relationships of TRPM4-like currents induced by 1.7 μM intracellular Ca\(^{2+}\) in control (n = 9) and 24 h LPS-exposed (n = 9) microglial cells after 100 s and 350 s into the experiment.

### Discussion

**Character of non-activated microglial cells in culture**

In the present study more than 90% of the mouse microglial cells appeared in a ramified, rod- or round-shaped morphology from day 1 to day 7 after harvest from an astrocyte coculture and the shape of the cells remained relatively stable. Resting microglia in vivo are thought to primarily express inward rectifying potassium currents (I\(_{\text{IRK}}\)) and no significant delayed outward rectifying potassium currents (I\(_{\text{DRK}}\)). Increasing the expression of I\(_{\text{DRK}}\) in favour of I\(_{\text{IRK}}\) upon activation (Norenberg et al., 1994; Eder, 1998; Walz & Bekar, 2001). In our cultures, the initial expression pattern of potassium currents revealed that the majority of cells expressed both types of currents and about some 30% of cells had only I\(_{\text{DRK}}\), indicating that the microglia were already somewhat preactivated in the astrocyte coculture (Schmidtmauer et al., 1994) and/or the harvesting procedure induced some activation. We suspect that serum levels are an important factor, since initial experiments in which we kept the levels of FBS at 10% in both co- and subculture, most of the cells showed already significant signs of activation such as amoeboid ‘fried egg’-shaped morphology, often with prominent I\(_{\text{DRK}}\) (data not shown). However, coculturing cells with 10% FBS in basal modified Eagle’s medium (BME) and reducing FBS to 5% in the subculture improved the yield of resting cells and most microglia were ramified rod-shaped within 3 days; most cells had little or no I\(_{\text{DRK}}\) but prominent I\(_{\text{IRK}}\), indicating largely resting cultured microglia (Kettenmann et al., 1990, 1993). In contrast, Eder et al. (1999) and Nakamura et al. (1999) obtained amoeboid-shaped microglia using Dulbecco’s modified Eagle’s medium (DMEM) plus 10% FBS for microglia/astrocyte coculture and DMEM plus 10% or 2% FBS for the subculture (Eder et al., 1999; Nakamura et al., 1999). These cells revealed prominent I\(_{\text{IRK}}\) but no I\(_{\text{DRK}}\) (Eder et al., 1999). Lombardi et al. (2003) used BME instead of DMEM under serum-free conditions (BME also lacks l-glycine (Gly) and l-serine (Ser)). Under Gly–Ser-free serum-free conditions, microglia displayed a round morphology, whereas in the presence of 5 μM Gly.
and 25 μM Ser they revealed ramifications (Lombardi et al. 2003). These results show that the morphological and electrophysiological character of cultured microglial cells depend on the environmental condition, and the electrophysiological properties do not necessarily correlate completely with the morphology in culture.

Resting microglia in vivo are highly ramified and convert into amoeboid macrophage-like cells when activated (Thomas, 1992; Vilhardt, 2005). As tissue preparations represent traumatic injuries that result in activated microglia, physiological aspects of resting microglial function and early activation in vivo remains largely elusive. The probably closest representation of truly resting microglia in vivo are ramified microglial cells found in acutely isolated brain slices. A few hours after preparation, microglial cells of rat hippocampal brain slices change their morphology from ramified to amoeboid (Stence et al. 2001). Interestingly, and in contrast to cultured cells, microglia in rat brain slices revealed almost no inward and voltage-gated outward potassium currents (Boucsein et al. 2000). Within 12 h after facial nerve axotomy, microglia in the facial nucleus expressed a prominent I_{IRK} and thus acquired the physiological properties of cultured microglial cells. Within 24 h of axotomy, the cells expressed I_{DRK}, which is typical for lipopolysaccharide (LPS)-exposed cultured microglia. Similar results have been obtained after a permanent middle cerebral artery occlusion (MCAO) in the rat brain (Lyons et al. 2000). It thus appears that the activation of microglial cells in vivo proceeds in two steps, first characterized by the expression of I_{IRK} and later by I_{DRK}. Since cultured non-activated microglial cells reveal almost exclusively I_{IRK} they represent a similar physiology as the early activated stage (Boucsein et al. 2000; Lyons et al. 2000), which is a result similar to the highly motile microglia invading the brain in early development, as these cells also express just I_{IRK} (Brockhaus et al. 1993). Thus, cultured microglial cells might represent an early intermediate stage between resting and activated microglia that still allows the study of further microglia activation.

### Potassium currents (I_{IRK} and I_{DRK}) after LPS exposure

Microglial cells appear in different shapes and express a distinct pattern of ion channels according to their status of activation. In our study, non-activated cultured microglia appeared in a ramified, rod- or round-shaped morphology with prominent I_{IRK}. After exposure to 1 μg ml⁻¹ LPS, cells responded with an increase in cell capacitance (surface area) and exhibited an amoeboid, ‘fried egg’-shaped morphology (see Fig. 1C and D). While I_{IRK} constantly decreased, I_{DRK} reached maximal expression within 6 h but decreased thereafter again (see Fig. 2B and G). This result is in agreement with the general consensus that resting cultured microglia primarily express I_{IRK} and recruit I_{DRK} after exposure to LPS (Kettenmann et al. 1990, 1993; Norenberg et al. 1992, 1994; Illes et al. 1996; McLarnon et al. 1997; Draheim et al. 1999). The I_{IRK} is suggested to be of the Kir2.1-like subtype (Newell & Schlichter, 2005) and LPS-activated microglia express mRNA and proteins for the delayed outward rectifier potassium channels Kv1.3 and Kv1.5 (Khanna et al. 2001). While pharmacological evidence indicates that the channel might be of the Kv1.3 subtype (Pyo et al. 1997; Visentin & Levi, 1998; Cayabyab et al. 2000; Khanna et al. 2001), immunological data by Pyo et al. (1997) suggested that the LPS-induced outward current is probably due to the Kv1.5 subtype and more recent studies revealed that LPS-induced I_{DRK} is reduced in Kv1.5⁻/⁻ knock-out mice. Since K⁺ currents in antisense oligonucleotide-treated cultured mouse microglial cells are affected (Pannasch et al. 2006), it seems possible that both Kv1.5 as well as Kv1.3 might be expressed in microglia.

Less is known about the physiological functions of I_{IRK} and I_{DRK} in microglial cells. I_{DRK} seems to be somehow correlated to NO release, since knock-out or block of Kv1.5, but not Kv1.3, resulted in a significant decrease in LPS-induced NO release in culture (Pyo et al. 1997; Pannasch et al. 2006), and Kv1.5 expression in vivo precedes the expression of inducible nitric oxide synthase (iNOS) (Jou et al. 1998). In addition, the Kv1.3 inhibitor agitoxin-2 reduced the microglial respiratory burst, a metabolic cascade that generates antimicrobial superoxide and other reactive oxygen intermediates (Khanna et al. 2001). I_{IRK} and I_{DRK} are mostly discussed to stabilize the membrane potential and are involved in microglial proliferation (Chung et al. 1999; Kotecha & Schlichter, 1999; Eder, 2005; Pannasch et al. 2006). Since resting microglia in vivo are devoid of the potassium currents, their membrane potential is relatively positive (Boucsein et al. 2000). In a first step of LPS-induced activation, I_{IRK} appears (Boucsein et al. 2000; Lyons et al. 2000) and the membrane potential becomes more negative. Hence, microglia cell activation correlates with an increase of the driving force for Ca²⁺ into the cell. This also applies to non-activated microglial cells in culture, as they already express I_{IRK}. In the absence of I_{DRK}, even a small inward current can lead to a large membrane depolarization. In a second step, I_{DRK} appears in microglia in vivo (Boucsein et al. 2000; Lyons et al. 2000) as well as in cultured microglia (Kettenmann et al. 1990, 1993; Norenberg et al. 1992, 1994; Illes et al. 1996; Newell & Schlichter, 2005), stabilizing the negative membrane potential and the driving force for Ca²⁺ into the cell. Franchini et al. (2004) observed that inhibition of I_{IRK} with Ba²⁺ significantly reduced the Ca²⁺ influx following receptor activation (Franchini et al. 2004). Our results reveal that following an initial peak after 6 h of LPS exposure, the amplitude of I_{IRK} decreased again within 24 h to almost basal level. There was also
a parallel decrease in the amplitude of $I_{\text{DRK}}$. Both effects would favour a more depolarized membrane potential and decreased driving force for Ca$^{2+}$ into the cell. After about 48 h, the expression pattern returned to that observed in microglia prior to LPS exposure in culture, with most cells expressing both $I_{\text{DRK}}$ and $I_{\text{IRK}}$, but with relatively small amplitudes (see Fig. 2B and G). The cell shape, however, remained amoeboid. The transient increase in $I_{\text{DRK}}$ and the associated potential for enhanced Ca$^{2+}$ driving force into the cell indicates some importance for Ca$^{2+}$ signalling, especially during the first 6 h after LPS-induced activation.

**Time course of LPS-induced effects**

Most studies in cultured microglia assess the effects of LPS 24 h or later after exposure, a time where the most prominent electrophysiological change in our study, the increase of $I_{\text{DRK}}$, has already declined (see Fig. 2G). In addition, the most prominent changes in [Ca$^{2+}$], caused by LPS occur over a time window that is not typically studied by most investigations. After a delay of 40–50 min, LPS induces a prolonged increase in the intracellular Ca$^{2+}$ levels, followed by a transient undershoot lasting several hours, before returning to normal levels (see Fig. 1F and G). Thus, our results show that the most dramatic changes in terms of basic Ca$^{2+}$ take place in the first 3 h and in terms of potassium currents in the first 3–6 h after LPS exposure. Intracerebroventricular injection of LPS in mice induced a sharp peak of interleukin-6 (IL-6) and monocyte chemotactic protein-1 (MCP-1) production at about 4 h, returning to baseline after about 16 h (Lund et al. 2006). Nakamura et al. (1999) also reported the most dramatic production of IL-6 as well as IL-1-$\beta$ and TNF-$\alpha$ in the first 6 h after LPS exposure (Nakamura et al. 1999). Interestingly, IL-6 and IL-1-$\beta$ induction remained elevated, TNF-$\alpha$ expression declined after 12 h. These LPS-induced events thus occur in a similar time frame as $I_{\text{DRK}}$ and the resulting increase in Ca$^{2+}$ signalling ability seen in our study. Nakamura et al. (1999) also showed that LPS induced a transient change of morphology from round amoeboid to process-bearing bipolar and back to round cells, where the cells reached maximum size after 6 h and returned to baseline after 24 h (Nakamura et al. 1999). In contrast, we observed a continuous increase of cell capacitance and a consistent morphological change from ramified to amoeboid over a period of 48 h after LPS exposure (see Fig. 1C and E). These differences in morphology and time course might be due to the fact that Nakamura et al. (1999) studied rat microglial cells grown in DMEM and we studied mouse microglial cells grown in BME medium.

### $I_{\text{CRAC}}$ in cultured microglial cells

Ca$^{2+}$ signalling is widely used as a central mechanism for numerous cellular functions in other immunocompetent cells. However, the involvement of Ca$^{2+}$ and the role of different Ca$^{2+}$ signalling mechanisms in microglial cells are largely unknown. Microglial cells express several receptors such as purinergic P2Y (James & Butt, 2002; McLarnon, 2005; Light et al. 2006), adrenergic $\alpha$1 (Mori et al. 2002), muscarinic (Whittingmore et al. 1993; Zhang et al. 1998) endothelin (Moller et al. 1997; McLarnon et al. 1999), thrombin (Moller et al. 2000), platelet-activating factor (Mori et al. 1996) and cytokine/chemokine receptors (Boddeke et al. 1999; Francis et al. 2002; Shideman et al. 2006), coupled to the second messenger inositol 1,4,5-trisphosphate (IP$_3$) and mediating release of Ca$^{2+}$ from intracellular stores. Ca$^{2+}$ release often is followed by a prolonged secondary phase that is due to store-operated (capacitative) Ca$^{2+}$ entry (SOCE) (Putney, 1986). The best characterized SOCE current and probably the main Ca$^{2+}$ influx pathway in immunocompetent cells is the Ca$^{2+}$ release-activated Ca$^{2+}$ current ($I_{\text{CRAC}}$) (Hoth & Penner, 1992). In microglial cells, SOCE has so far mainly been studied via Ca$^{2+}$ imaging techniques (Toescu et al. 1998; Khoo et al. 2001; Choi et al. 2003), only few publications showing microglial $I_{\text{CRAC}}$ measured with the whole-cell patch-clamp technique (Norenberg et al. 1997; Hahn et al. 2000). In the present study we show that the amplitude of $I_{\text{CRAC}}$ in cultured microglial cells decreases significantly with time of activation and LPS exposure. In contrast to the transient increase in $I_{\text{DRK}}$ with the peak after 6 h, $I_{\text{CRAC}}$ continuously decreased, indicating an immediate down-regulation of Ca$^{2+}$ influx after LPS-induced activation. This suggests that either increasing the driving force for Ca$^{2+}$ is not the major purpose of LPS-induced increase of $I_{\text{DRK}}$, or $I_{\text{CRAC}}$ is not its most important addressee. SOCE is probably the major but not the only way of Ca$^{2+}$ influx into microglial cells. There is no evidence for voltage-gated Ca$^{2+}$ channels in microglial cells, but they reportedly express several other Ca$^{2+}$-permeable ion channels such as the AMPA (3-amino-3-hydroxy-4-methyl-4-isoxazole propionate) receptor channel, a subtype of the ionotropic glutamate receptor, with a relatively low Ca$^{2+}$ permeability (Noda et al. 2000), TRPM2 and TRPM7, members of the melastatin-related transient potential receptor channels (Wang et al. 2000; Jiang et al. 2003) and purinergic P2X receptors (Visentin et al. 1999; Wang et al. 2000; Farber & Kettenmann, 2006). In terms of intracellular Ca$^{2+}$, LPS exposure also induces Ca$^{2+}$ transients in cultured microglial cells (see Fig. 1F, unidentified mechanism), possibly resulting from caffeine-sensitive Ca$^{2+}$ release (Bader et al. 1994) and/or dependent on unidentified Ca$^{2+}$ influx channels (Herms et al. 1997; Choi et al. 2002; Yi et al. 2005).
Besides voltage-gated potassium channels, other ion channels such as Ca\(^{2+}\)-activated K\(^+\) channels (Kausal et al. 2007), H\(^+\) channels (Klee et al. 1998, 1999), non-selective cation channels (Schilling et al. 2004), and Cl\(^-\) channels (Schlichter et al. 1996; Eder et al. 1998) have also been shown to be involved in further activation or proliferation of cultured microglial cells, although their temporal expression patterns during the activation process have not yet been characterized. Our study additionally reveals a Ca\(^{2+}\)-activated TRPM4-like current in non-activated cultured mouse microglial cells. Ca\(^{2+}\)-activated cation channels such as TRPM4 and TRPM5 are widely expressed and proposed to be involved in membrane depolarization (Launay et al. 2002; Prawitt et al. 2003; Guinamard et al. 2004). While I\(_{IRK}\) and I\(_{CRAC}\) support the driving force for Ca\(^{2+}\) through negative membrane potentials, incoming Ca\(^{2+}\) might depolarize the microglial cells via activation of the TRPM4-like current, thus reducing the driving force and regulating the Ca\(^{2+}\) influx negatively. In electrically non-excitable Jurkat T lymphocytes, suppression of TRPM4 disregulates receptor-induced Ca\(^{2+}\) oscillations leading to enhanced IL-2 production due to sustained increases in cellular Ca\(^{2+}\) levels (Launay et al. 2004). In microglia, however, besides a slightly faster activation and a slightly stronger outward rectification, LPS exposure did not significantly change the character or size of the Ca\(^{2+}\)-activated TRPM4-like I\(_{CAN}\). We therefore propose that LPS-induced down-regulation of I\(_{IRK}\) and I\(_{CRAC}\) reduces the cell’s capacity to produce significant Ca\(^{2+}\) influx upon receptor stimulation and results in decreased sensitivity to additional exogenous stimulation. In this scenario, I\(_{CAN}\) does not need to be affected, as its activity would automatically be adjusted due to the diminished calcium influx capacity of the cell.

The mechanism(s) of LPS-induced down-regulation of I\(_{IRK}\) and I\(_{CRAC}\) and transient up-regulation of I\(_{DRK}\) are not known yet. However, the activation of microglial Toll-like receptor-4 (TLR-4) by LPS results in the induction of an array of genes that are involved in initiation or regulation of the inflammatory response (Hoshino et al. 1999; Lee & Lee 2002). LPS-induced CD40 expression involves activation of the transcription factor nuclear factor-κB (NF-κB) and signal transducer and activator of transcription 1α (STAT-1α), which is activated by the endogenous production of interferon-β (IFN-β) (Qin et al. 2005). The extended delayed transient Ca\(^{2+}\) increase after LPS exposure observed in this study (see Fig. 1F) might also be involved in nuclear gene regulation, since it is known that intracellular Ca\(^{2+}\) signals can trigger gene expression.


Temporal changes in LPS-exposed cultured microglia


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Lipopolysaccharide-induced down-regulation of Ca2+ release-activated Ca2+ currents (ICRAC) but not Ca2+-activated TRPM4-like currents (ICAN) in cultured mouse microglial cells
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