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Serum and Glucocorticoid–Regulated Kinase 1 Regulates Neutrophil Clearance during Inflammation Resolution


The inflammatory response is integral to maintaining health by functioning to resist microbial infection and repair tissue damage. Large numbers of neutrophils are recruited to inflammatory sites to neutralize invading bacteria through phagocytosis and the release of proteases and reactive oxygen species into the extracellular environment. Removal of the original inflammatory stimulus must be accompanied by resolution of the inflammatory response, including neutrophil clearance, to prevent inadvertent tissue damage. Neutrophil apoptosis and its temporary inhibition by survival signals provides a target for anti-inflammatory therapeutics, making it essential to better understand this process. GM-CSF, a neutrophil survival factor, causes a significant increase in mRNA levels for the known anti-apoptotic protein serum and glucocorticoid–regulated kinase 1 (SGK1). We have characterized the expression patterns and regulation of SGK family members in human neutrophils and shown that inhibition of SGK activity completely abrogates the antiapoptotic effect of GM-CSF. Using a transgenic zebrafish model, we have disrupted sgk1 gene function and shown this specifically delays inflammation resolution, without altering neutrophil recruitment to inflammatory sites in vivo. These data suggest SGK1 plays a key role in regulating neutrophil survival signaling and thus may prove a valuable therapeutic target for the treatment of inflammatory disease.

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Abbreviations used in this article: AUR, aurora kinase; DMOG, dimethyl oxaloylglycine; dpf, days postfertilization; EGFP, enhanced GFP; hpi, h postinjury; NDRG, N-myc downstream regulated; McI-1, myeloid cell leukemia-1; PDK, phosphoinositide-dependent kinase; SGK, serum and glucocorticoid-regulated kinase.

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messenger phosphatidylinositol 3,4,5-triphosphate and downstream phosphorylation of AKT (15, 16), which in turn phosphorylates a wide range of cellular substrates with diverse cellular effects (17). AKT is seen as a central player in the transduction of cell surface signals to the core apoptotic machinery, and AKT inhibitors have been shown to delay neutrophil apoptosis (18). However, IMLP receptors also signal via PI3K activation and activate AKT but without affecting neutrophil apoptosis (19). Therefore, there is a dissociation of apoptosis signaling and AKT activation, suggesting roles for other signaling molecules in addition to PI3K activation in apoptosis regulation.

Activation of the JAK/STAT pathway downstream of GM-CSF stimulation is thought to act predominantly via transcriptional effects. Traditionally, neutrophils were thought not to be subject to transcriptional regulation, but there is evidence of considerable regulation of neutrophil mRNA repertoire by inflammatory stimuli (including GM-CSF) (20, 21), with potential further regulation by microRNAs (22). In one study, mRNA changes in neutrophils were detected by microarray following GM-CSF stimulation (21). One of the most upregulated mRNAs was that of the known antiapoptotic protein serum and glucocorticoid–regulated kinase 1 (SGK1), which, with GM-CSF stimulation, was upregulated 13.2-fold. This protein had previously been shown to be regulated by GM-CSF and also upon treatment with other neutrophil survival agents such as LPS and TNF-α (23). SGK1 shares 54% amino acid homology with AKT (24) and is also regulated by phosphorylation downstream of PI3K (25). We hypothesized that SGK1 might be an important link between extracellular antiapoptotic stimuli and the downstream apoptosis machinery in neutrophils.

Materials and Methods

Reagents

Reagents used were qVD-OPh (R&D Systems, Abingdon, U.K.), GM-CSF (PeproTech, London, U.K.), dimethylxoylooylglycine (DMOG), LPS, ATPs, and the DMSO control (all from Sigma-Aldrich, Poole, U.K.). Three SGK inhibitors were used: GK650394 (Tocris Bioscience, Bristol, U.K.), GSK1558634A, and GSK398689A (GlaxoSmithKline, Hertfordshire, U.K.). The sgk1 morpholino and standard control morpholino were from Gene-tools (Philomath, OR).

Purification of peripheral blood neutrophils

Peripheral venous blood was taken from healthy volunteers in accordance with the specific approval of the South Sheffield Research Ethics Committee (reference number STH13027), and neutrophils were prepared as described previously (26). Negatively selected neutrophil preparations were >98% pure. Apoptotic neutrophils were counted by an observer blind to the experimental condition, from cytospins stained with Quick-Diff (Gentaur, Cambridge, U.K.).

Protein detection by Western blot analysis

Samples were prepared from ∼5 × 10⁶ neutrophils as previously described (26) or from 30 pooled 5-d postfertilization (dpf) zebrafish embryos, and Western blotting was performed according to standard protocols (27) using a Protein 2 gel assembly (Bio-Rad, Hemel Hempstead, U.K.) and transferred to Hybond-P polyvinylidene difluoride membrane (GE Healthcare Life Sciences, Bucks, U.K.) using a Trans-Blot semi-dry blotter (Bio-Rad). Abs used were anti-SGK (number 3217; Cell Signaling Technology, Hertfordshire, U.K.) using an anti-SGK antibody (A2066; Sigma-Aldrich) at 1:2000 and polyclonal goat anti-rabbit (1:1000), anti–myeloid cell leukemia-1 (Mcl-1) (sc-819; Santa Cruz Biosciences, Santa Cruz, CA) at 1:1000, anti–phospho-N-myris downstream regulated (NDRG)-1 (number 3217; Cell Signaling Technology) at 1:1000, anti-total NDRG-1 (number 5196; Cell Signaling Technology) at 1:1000, or anti-actin (A2066; Sigma-Aldrich) at 1:2000 and polygonal goat anti-rabbit secondary Ab (DakoCytomation, Cambridge, U.K.) at 1:2000 (1:5000 for anti-actin). Densitometry was performed using ImageJ as described previously (26).

PCR analysis of SGK mRNA isoforms and morpholino knockdown

RNA was extracted from ∼7 × 10⁶ human neutrophils (>96% purity) or 10–15 zebrafish larvae, using TRIzol reagent (Invitrogen, Paisley, U.K.), according to the manufacturer’s instructions. RT-PCR used Superscript III RT Enzyme (Invitrogen), and PCR used Finnzymes Phusion (New England Biolabs, Hertfordshire, U.K.) and was carried out in a C1000 Thermal Cycler. Primers used are shown in Supplemental Table I.

Zebrafish husbandry and assays

Adult fish were maintained on a 14:10-h light/dark cycle at 28°C in the U.K. Home Office–approved facilities. Experiments were performed using the Tg(mpx:GFP)i114 line, which specifically labels neutrophils with GFP (28), or the Tg(lyz:PHAK-EGFP)1277, which detects PI3K activation in neutrophils by recruitment of the enhanced GFP (EGFP)-tagged pleckstrin homology domain of AKT to phosphatidylinositol 3,4,5-triphosphate in the membrane (29). Larvae were collected and maintained according to standard protocols (30). Assays of neutrophil recruitment to tailfin injury were performed as described previously (28). For analysis of total neutrophil number, larvae were mounted in 1% agarose and imaged using the ×2 objective on a Nikon Eclipse TE2000U Inverted Microscope; neutrophils were counted blind, using ImageJ and Velocity (PerkinElmer, Cambridge, U.K.). Neutrophil apoptosis rates were assessed in PFA-fixed larvae, followed by Tyramide Signal Amplification (TSA) staining (TSA-Plus; PerkinElmer) and ApopTag Red In Situ Apoptosis Detection Kit (TUNEL) (Millipore, Herts, U.K.) as described previously (31).

Agilent microarray expression analysis

Six adult fish (from an mpox:GFP background) were acclimated using a scalpel and passed through a series of micrometer meshes to further dissociate the cells. Cells were sorted by FACS analysis into those cells showing appropriate side scatter (of light) and forward light scatter to be neutrophil-like and further sorted into GFP-positive and -negative sets. GFP-negative cells were used as a control. RNA was extracted from sorted cells using the mirVana kit as per manufacturer’s instructions (Ambion, Huntingdon, U.K.). Microarray analysis was performed using a Zebrafish (V3) Gene Expression Microarray containing 43663 probes (Agilent Technologies, Amstelveen, The Netherlands) as described previously (32).

Mass spectrometric analysis of drug penetration of larvae

Three dpf zebrafish samples (20 fish per time point) were sonicated (Soniprep 150; M&E, Sussex, U.K.) as described previously (33). Homogenized zebrafish samples were extracted by protein precipitation with the addition of 750 μl acetonitrile containing a structural analog internal standard. Samples were mixed and centrifuged at 2200 × g for 20 min. Liquid chromatography–tandem mass spectrometry analysis was performed using an API 4000 triple quadrupole mass spectrometer (AB Sciex) with an electrospray ionization source operating in positive ion mode. The UHPLC system incorporated a Jasco XLC dual pump system with a gradient elution method using acetonitrile +0.1% formic acid (v/v) and water +0.1% formic acid (v/v) mobile phase and a Phenomenex Kinetex analytical column (C18, 2.6 μm, 50 × 2.1 mm). Samples were analyzed against calibration standards prepared in a control zebrafish homogenate matrix over a concentration range of 1–5000 ng/ml, with an assay LLOQ of 1 ng/ml. We estimated the volume of a zebrafish larva to be 0.0375 μl.

Statistical analyses

Data were analyzed (P Prism 5.0; GraphPad Software) using either unpaired, two-tailed Student t tests for comparisons between two groups or one-way ANOVA with Bonferroni post-test adjustment for other data, except where indicated in the figure legend.

Results

Multiple SGK isoforms are expressed in neutrophils and regulated by GM-CSF

Kobayashi et al. (21) showed GM-CSF stimulation increased levels of SGK1 mRNA and prevented time-dependent decreases in SGK1 protein levels. There are, however, three SGK genes present in humans: SGK1, SGK2, and SGK3, each sharing 80% homology at their catalytic domain (34). In addition, there are four alternatively spliced isoforms of SGK1 and two for both SGK2 and 3 (Supplemental Fig. 1A). We determined the expression profile of these different genes and isoforms in ultrapure human neutrophils (35). Using specific primer pairs in RT-PCRs, we identified full-length isoforms of SGK1, SGK2, and SGK3 mRNA in human neutrophils (Fig. 1A). SGK1 mRNA was detected at higher levels
following GM-CSF stimulation at early time points, whereas SGK2 expression was unaltered with GM-CSF stimulation. SGK3 mRNA levels, in contrast to previous reports (34), appeared to be increased initially but declined over time. Because GM-CSF regulation was largely confined to SGK1, we examined expression of the different isoforms of this gene. We aligned the sequences of the four SGK1 isoforms and identified the important domains and regulatory regions of the gene (Supplemental Fig. 1B). We found that all isoforms varied only at their amino termini, where amino acids encoded by the first exons varied between isoforms both in length and sequence, with isoform 2 having additional exons. Functional domains within the protein were maintained between isoforms excepting the first 60 aa; these have been identified as playing a role in the ubiquitination and degradation of SGK1 (36). PCR analysis shows mRNAs for all SGK1 isoforms are regulated by GM-CSF (Fig. 1B) at early time points, although not at 20 h.

To confirm changes in mRNA expression were paralleled by changes at the protein level, we analyzed the change in SGK1 protein levels over time and following GM-CSF stimulation. We found, in agreement with Kobayashi et al. that GM-CSF prevented the reduction in SGK1 levels over time (Fig. 1C, 1D) in parallel with increases in neutrophil survival (Fig. 1E). Although the Ab used detects all members of the SGK protein family (SGK1, SGK2, and SGK3), no bands corresponding to full-length SGK2 or SGK3 were identified. A band was routinely identified corresponding to full-length SGK1 (isoform 1), which has a predicted size of 49 kDa. To investigate whether the different levels of SGK1 detected were due to its decrease over time or merely due to the different numbers of viable neutrophils at the time points analyzed, we used the caspase inhibitor, Q-VD-OPh, to prevent all neutrophil death (26). Following Q-VD-OPh treatment, SGK1 levels with or without GM-CSF stimulation were unchanged from DMSO-treated control levels, despite the almost complete absence of apoptosis. This suggests that levels of SGK1 do not fall as a consequence of engagement of neutrophil apoptotic pathways (Supplemental Fig. 2).

**SGK1 inhibition blocks GM-CSF–induced human neutrophil survival**

SGK1 is upregulated at both the mRNA and protein level with GM-CSF treatment. We hypothesized that this upregulation was functionally important and that the activity of SGK1 contributed to GM-CSF–induced neutrophil survival. To test this hypothesis, we studied the effects on neutrophil apoptosis of the only commercially available inhibitor of SGK enzymes, GSK650394. GM-CSF–induced neutrophil survival was clearly seen at 8 h of culture, but with addition of 10 μM GSK650394, this effect was totally abrogated (Fig. 2A). GSK650394 also increased constitutive neutrophil apoptosis, suggesting that the compound was directly influencing neutrophil lifespan. To confirm the caspase dependence of the morphological changes of apoptosis observed in these experiments, the pan-caspase inhibitor qVD-OPh was shown to prevent all cell death (Fig. 2B).

To investigate whether the inhibition of neutrophil survival signaling by GSK650394 was specific to GM-CSF survival, we investigated its effect on a number of other neutrophil survival stimuli including activation of hypoxia-inducible factor signaling (mimicking hypoxia, induced in this study by the chemical DMOG) (31), LPS (37), and ATPγs (7). All survival factors reduced the amount of apoptosis compared with the control, although to a lesser degree than GM-CSF (Fig. 2C). GSK650394 treatment abrogated the survival induced by GM-CSF and hypoxia but did not affect that induced by LPS and ATPγs (Fig. 2C), indicating that SGK1 is important to some, but not all, survival pathways.

To further probe the mechanism by which SGK1 inhibition might lead to neutrophil apoptosis, we tested whether SGK1 inhibi-
model for visualizing individual inflammatory cell behaviors in a simple in vivo model of neutrophilic inflammation. Our preferred mechanisms. Therefore, we wished to study the effect of Sgk1 inhibition numbers of apoptotic neutrophils overwhelm clearance mechanisms. This was reflected in a reduction in the dis-

Acceleration of apoptosis in vitro may not always correspond to in vivo, in part through an increase in neutrophil apoptosis. By GM-CSF and DMOG but not that by LPS and ATPγs (\(p < 0.05, n = 3\)).

FIGURE 2. Chemical inhibition of SGK1 abrogates neutrophil survival through an increase in apoptosis. Human neutrophils were treated as indicated for 8 h, and percentage apoptosis was scored by cytospin analysis. (A) GSK650394 causes an increase in apoptosis rates, and the 10 μM concentration significantly inhibits GM-CSF induced neutrophil survival (\(t\) test, \(*p < 0.05, n = 5\)). (B) Caspase inhibition prevents all neutrophil death (\(t\) test, \(*p < 0.05, n = 4\)). (C) Neutrophil survival factors lower apoptosis rates at 8 h, and GSK650394 treatment abrogates survival caused by GM-CSF and DMOG but not that by LPS and ATPγs (\(*p < 0.05, n = 3\)).

Sgk1 inhibition enhances the resolution of inflammation in vivo, in part through an increase in neutrophil apoptosis

Acceleration of apoptosis in vitro may not always correspond to acceleration of inflammation resolution in vivo, particularly if antiapoptotic factors predominate at the inflammatory site or large numbers of apoptotic neutrophils overwhelm clearance mechanisms. Therefore, we wished to study the effect of Sgk1 inhibition in a simple in vivo model of neutrophilic inflammation. Our preferred model for visualizing individual inflammatory cell behaviors in a genetically and pharmacologically manipulable organism is the transgenic zebrafish model established in our laboratory (28). This model allows direct visualization of vertebrate neutrophils during inflammation in vivo and has proven invaluable in the identification of unique features of neutrophil behavior (31, 38).

By 3 dpf, zebrafish larvae have a fully functioning innate immune system, and importantly for these experiments, the zebrafish \(sgk1\) gene is highly similar to the human gene in both amino acid sequence and conservation of key functional domains (Supplemental Fig. 1C). By microarray analysis of FACS-sorted zebrafish neutrophils, \(sgk1\) is present in zebrafish neutrophils at a level 7.84 times higher than in nonneutrophil cells, underlining its importance in this cell type.

To investigate whether the chemical inhibitor of human SGK1, GSK650394, could penetrate zebrafish at this larval stage, we incubated 3 dpf larvae with GSK650394 at 10 μM for an hour. We then subjected the larvae to mass spectrometric analysis as described in Materials and Methods. We measured 0.089 nmol compound per larva, or 237 μM, confirming considerable concentration of compound within each larva. To further test whether the compound could successfully inhibit zebrafish Sgk1, we studied its phosphorylation activity in vivo. Ndrg1 is known to be phosphorylated solely by SGK1 (39), and thus, its phosphorylation can be used as a read out for SGK1 activity. In larvae treated with GSK650394, there was a dose-dependent reduction in phosphorylated Ndrg1 without any effect on the total amount of Ndrg1 present (Fig. 3A). This indicates that GSK650394 successfully inhibits Sgk1 activity in our assays.

Inflammation is induced in 3 dpf zebrafish larvae by transection of the caudal fin (Fig. 3B), and the cellular component of the inflammatory response is quantified by counting the number of neutrophils present at the site of injury. In untreated larvae, recruitment of neutrophils to the site of injury occurs within the first 6 h postinjury (hpi), followed by spontaneous resolution within 24 h. In this model, GSK650394 added during peak inflammation caused specific reduction in neutrophil numbers (Fig. 3C, 3D), without altering numbers of neutrophils elsewhere in the animal (Fig. 3E).

To see whether the effects on inflammation resolution were mediated by induction of neutrophil apoptosis in vivo, we dual stained for endogenous neutrophil peroxidase activity and for dsDNA breaks as a marker for apoptosis using TUNEL. These experiments were performed by adding the compound at peak neutrophil number (6 hpi) and measuring apoptosis at 12 hpi during peak inflammation resolution. Neutrophil numbers were reduced significantly in these experiments compared with control (Fig. 3F). Rates of apoptosis were comparable to previous studies (31) and were significantly higher for the GSK650394 group (Fig. 3G). Interestingly, these effects were specific to inflammatory neutrophils, because rates of neutrophil apoptosis were not increased with GSK650394 treatment of uninjured larvae (data not shown).

\(GSK650394\) inhibits the recruitment of neutrophils to the site of injury through disruption of the direction and speed of neutrophil chemotaxis

To test whether the SGK1 inhibitor had any effect on other aspects of neutrophil function in vivo, we assessed the effects of GSK650394 on recruitment assays in the injured transgenic zebrafish model. Using Velocity software, we tracked neutrophils as they moved toward the site of tailfin injury (Fig. 4A) and saw a marked reduction in the movement of neutrophils treated with GSK650394. Further analysis revealed that this was due to a reduction in neutrophil speed (Fig. 4B), whereas the meandering index (displacement divided by path length) of neutrophils was unaffected (Fig. 4C). We noted that many neutrophils remained in one area, extending and retracting lamellipodia without making any directional movements. This was reflected in a reduction in the displacement of neutrophils toward the wound in GSK650394-treated larvae (Fig. 4D). In addition, the bearing at which neutrophils moved is significantly different after GSK650394 treatment:
control neutrophils preferentially migrate toward the wound but GSK650394-treated larvae do not (Fig. 4E).

**Genetic inhibition of sgk1 has a different anti-inflammatory phenotype to pharmacological inhibition of Sgk1**

Pharmacological modulators of neutrophil function are prone to confounding results by off-target effects, and genetic confirmation of the phenotype is essential to confirm potential drug targets. Efficient knockdown of gene function in zebrafish can be achieved by injection of morpholino-modified antisense constructs into the fertilized egg (40). This can lead to altered expression of the target gene for many days. We therefore designed a “morpholino” to alter the pre-mRNA splicing of the \textit{sgk1} gene by targeting the splice site of intron 5 and causing intron inclusion, introducing a premature stop codon and leading to protein truncation. Effective gene knockdown was confirmed by RT-PCR analysis on RNA extracted from morphant larvae, with maintenance of the intron seen as a 385-nt shift in the \textit{sgk1} band detected (Fig. 5A).

To isolate and identify the specific stage of the inflammatory response at which Sgk1 inhibition was having its effect, we analyzed neutrophil number at the site of injury over the course of an entire inflammatory response by performing neutrophil counts at 2, 4, 6, 8, 12, and 24 hpi. In GSK650394-treated larvae, there was a clear inhibition of neutrophil recruitment (Fig. 5B). To investigate whether reduction in neutrophil recruitment was due to specific inhibition of Sgk1 we repeated this time course using \textit{sgk1} morpholino injected larvae. We found that genetic knockdown of \textit{sgk1} caused an increase in the resolution of the inflammatory response (Fig. 5C), without affecting recruitment or total neutrophil number (Fig. 5D). Additional confirmation of the importance of
Sgk1 levels on resolution of inflammation was obtained by separating larvae into groups showing the highest and lowest rates of inflammation resolution. The group having fewer neutrophils had better knockdown of sgk1 (Fig. 5E), confirming its importance in regulating inflammation resolution.

**GSK650394 inhibits neutrophil recruitment by off-target effects, in part through the inhibition of PI3K**

Detailed analysis of neutrophil recruitment behavior in sgk1 morphants revealed no difference in the morphant neutrophils’ speed of movement (Fig. 5F) or their ability to follow the chemotactic gradient (Fig. 5G–I), suggesting GSK650394 might be acting on a target other than Sgk1 to block chemotaxis. The profound effect on neutrophil recruitment and differences in the shape of GSK650394-treated neutrophils (data not shown) led us to hypothesize that these effects might relate to off-target inhibition of the PI3K pathway. This was possible as GSK650394 was known to inhibit >30 enzymes, other than SGK1, with a pIC50 of >6 (data not shown). To further investigate this hypothesis, the effect of PI3K inhibition on neutrophil recruitment was studied in the zebrafish model. PI3K inhibition reduces the number of neutrophils recruited to a site of injury in a similar manner to GSK650394 (Fig. 6A). A more detailed investigation of neutrophil chemotaxis shows that this reduction in recruitment is due to an inhibition of neutrophil speed (Fig. 6B), similar to that seen with Sgk1 inhibition. However, in contrast to findings with GSK650394-treated larvae, the bearing at which neutrophils moved was unaffected (Fig. 6C). Furthermore, using a PHAkt-EGFP line (29) to indicate the subcellular localization of phosphoinositides produced by PI3K activity, we investigated whether there were changes in PI3K activity in response to GSK650394 or Sgk1 knockdown. To quantify PI3K activity in individual cells in vivo, we used an assay we had previously developed to quantify PI3K activity in neutrophils in response to pharmacological treatments (29). This assay gives a numerical value of the cell polarization as indicated by PHAkt-EGFP distribution within neutrophils. Using this system, we were able to show that both PI3K inhibitors and GSK650394 reduced the polarity index (Fig. 6D, 6E) whereas genetic manipulation of Sgk1 did not (Fig. 6F).

This phenotype demonstrates the complexity of understanding off-target pharmacological inhibition, with only part of the effect of pharmacological Sgk inhibition likely to act via the PI3K pathway while underscoring the importance of genetic confirmation for all inhibitor studies.

**Highly specific SGK1 inhibitors block GM-CSF induced neutrophil survival and also lower neutrophil number at an in vivo site of injury**

We have shown that sgk1 genetic inhibition removes neutrophils from a site of inflammation; however, for this to be useful in a clinical situation, Sgk1 inhibition would have to be achieved using a chemical inhibitor. We have seen that GSK650394 has off-target effects and would not fulfill this role; we therefore used two potent SGK1 inhibitors from a chemical template distinct from that of GSK650394: GSK1558634A and GSK398689A. These compounds have a pIC50 of 8.2 and 8.8, respectively, with limited off-target effects. GSK1558634A inhibits only two other enzymes with a pIC50 > 6; these are aurora kinase (AUR)A, AURB; GSK398689A additionally inhibits YAK3 (GSK internal data). Treatment of human neutrophils with either of these new inhibitors removes the survival response to GM-CSF in a dose-dependent manner, with total abrogation by 100 μM (Fig. 7A–D). Importantly, these compounds had no effect upon constitutive apoptosis of human neutrophils.

Furthermore, zebrafish larvae treated with either GSK1558634A or GSK398689A after transection of the caudal fin show a signif-
icant and dose dependent reduction in the number of neutrophils at the site of injury (Fig. 7E, 7F). The ability of two additional, more specific, inhibitors of SGK1 to replicate both the inhibition of GM-CSF–induced neutrophil survival and the rapid resolution of the inflammatory response in vivo suggests that this occurs through inhibition of the SGK1 protein, not through off-target actions, adding support for a key role for SGK1 in the regulation of neutrophil lifespan during inflammation resolution.

Discussion

Previous work using human neutrophils has shown increased amounts of SGK1 mRNA and protein following GM-CSF stimulation (21); we have now produced genetic and pharmacological data showing the importance of SGK1 in controlling neutrophil lifespan in vitro and in vivo. We have not distinguished between new transcription and regulation of protein and mRNA stability, but we have shown by highly effective caspase inhibition that the changes in SGK1 protein level are independent of levels of apoptosis. Use of the only commercially available SGK inhibitor, GSK650394, together with newer more selective compounds and a morpholino against \( \text{sgk1} \), has shown it to play an important role in maintaining neutrophils at a site of injury. Sgk inhibition leads to rapid resolution of the inflammatory response without affecting neutrophil recruitment. SGK1 is therefore an important component of the pathways that link certain survival stimuli with the neutrophil apoptotic machinery. In other cell types, SGK1 is known to act downstream of PI3K and is activated by phosphoinositide-dependent kinase (PDK)1 through phosphorylation of Thr256 and by PDK2 via Ser422 (25, 41). We do not yet know completely how, once activated, SGK1 plays its antiapoptotic role; in other cell

![FIGURE 5. sgk1 inhibition enhances inflammation resolution without affecting neutrophil recruitment. Three-dpf mpx:GFP larvae were injured and treated as indicated, and neutrophil counts were performed at the time points shown. (A, C–E) One to 2 nl sgk1 morpholino was injected to larvae at the one cell stage. Knockdown disrupts the splicing of sgk1 premRNA causing intron 5 to be retained; this can be detected as a 385-bp band shift by PCR. (A) RT-PCR showing sgk1 knockdown from 1 to 3 dpf with addition of the sgk1 morpholino. (B) GSK650394 causes a highly significant inhibition of neutrophil recruitment to the site of injury (**\( p < 0.01 \), ***\( p < 0.005 \), \( n = 18 \) performed as three independent experiments). (C) The sgk1 morpholino increases resolution of the inflammatory response with a significant lowering of neutrophil number from 8 hpi (*\( p < 0.05 \), **\( p < 0.01 \), ***\( p < 0.005 \), \( n = 34 \) performed as three independent experiments). (D) Total neutrophil counts show no difference between the sgk1 morpholino and the control. (E) RT-PCR analysis of larvae separated after the morpholino time course into those with high and low neutrophil number at the site of injury show that larvae with fewer neutrophils show more complete morpholino knockdown. (F–I) mpx:GFP larvae were injected with 1–2 nl 0.25 mM sgk1 morpholino at the one cell stage and injured at 3 dpf, and a time-lapse video was taken for 1 h. Neutrophil chemotaxis was analyzed using Volocity. Neutrophils from the sgk1 morphants did not show any significant difference from the controls in their speed (F), meandering (G), or displacement toward the wound (H) (\( n = 11 \) performed as three independent experiments). (I) There is no difference in the bearing at which neutrophils move between the control and sgk1 morpholino–injected larvae (*\( p < 0.05 \), **\( p < 0.005 \), \( n = 11 \) performed as three independent experiments).]
types, it regulates this process through inactivation of the FOXO3a transcription factor (42) and upregulation of NF-κB signaling (43), both of which are important in neutrophils (44, 45). Interestingly, SGK1 phosphorylates and inactivates glycogen synthase kinase-3 (25), which is known to phosphorylate the key neutrophil antiapoptotic protein Mcl-1 leading to its destabilization and degradation (46), a key upstream event in neutrophil apoptosis (26). We now show that inhibition of Mcl-1 turnover in human neutrophils is a likely final mechanism for the antiapoptotic action of SGK1.

Chemical inhibition of Sgk enzymes with GSK650394 accelerates inflammation resolution and reduces neutrophil recruitment. Genetic ablation of Sgk1 alone has no effect on neutrophil recruitment. Studies of PI3K inhibition in vivo suggest that GSK650394, but not the genetic strategy, may act upstream of PI3K to modulate neutrophil recruitment, suggesting that inhibition of neutrophil recruitment is an off-target effect. It remains possible that the lack of effect on neutrophil recruitment with sgk1 morpholino could be due to incomplete knockdown of sgk1, as shown by the maintenance of a wild-type sgk1 band in our PCRs (Fig. 5A); the small amounts of wild-type sgk1 present may be sufficient for neutrophil recruitment, but not their maintenance, at a site of injury. More probable, given the different effects of treatment with the more specific inhibitors, is that the recruitment phenotype is an off-target effect of GSK650394. Over 30 enzymes are known to be inhibited by GSK650394 with a pIC50 = 6, including activin receptor-like kinase 5, AURB, calcium/calmodulin-dependent protein kinase kinase 1 and 2, cyclin dependent kinase-2, IL-2–inducible T cell kinase, JNK1, JNK3, and the class III PI3K, and vacuolar protein sorting 34, and it is likely that additional kinases that have not been included in these kinase profiling studies are also inhibited by GSK650394 (S. Farrow and W. Zuercher, unpublished data). Thus, there is considerable scope for significant off-target effects at the dose used. To overcome this limitation of the pharmacological approach, we used new inhibitors, GSK1558634A and GSK398689A. These compounds have a pIC50 of 8.2 and 8.8, respectively, inhibiting only three and four other enzymes with a pIC50 > 6. The fact that both compounds show the same pro-resolution phenotype as GSK650394 strongly supports the role of SGK1 in the regulation of neutrophil responses to survival signals. The effects on chemotaxis may relate to inefficient AKT2 recruitment following changes in PI3Kγ activation, because knockout of either gene causes frustrated chemotaxis (47, 48). Interestingly, the

![FIGURE 6. PI3K inhibition attenuates neutrophil recruitment through a reduction in speed. Three-dpf mpx:GFP larvae were pretreated for 2 h and injured, and a time-lapse image sequence was taken for 1 h. Neutrophil chemotaxis was analyzed using Velocity. (A) Both GSK650394 and LY294002 reduce the number of neutrophils recruited to a site of injury (**p < 0.0001, n = 12 performed as two independent experiments). (B) Neutrophil speed is significantly reduced with LY294002 treatment (***p < 0.0001, n = 15 performed as two independent experiments). (C) The bearing at which neutrophils migrate is not affected by PI3K inhibition (**p < 0.0001, **p < 0.05, n = 15 performed as two independent experiments). (D–F) Three-dpf PHAkt-EGFP larvae were pretreated for 2 h as indicated and subsequently injured. Neutrophils were imaged, and their polarity index calculated. (D) Representative images of treated neutrophils and fluorescence intensity per pixel graphs. (E) GSK650394 and LY294002 significantly reduce the polarity index of neutrophils (**p < 0.005, n = 22 performed on three separate occasions). (F) Injection of the sgk1 morpholino has no effect upon the polarity index of neutrophils (n = 26 performed on three separate occasions).]
The morphology of PI3Kγ knockout neutrophils is very similar to that seen in our time-lapse videos of GSK650394-treated neutrophils in the extending and retracting of lamellopodia.

The use of the zebrafish model of inflammation has allowed us to dissect the cellular consequences of SGK inhibition in ways that would not be possible in mammalian systems. The ability to dissociate effects of SGK inhibition on recruitment and neutrophil removal allows the pathway to be understood in detail. Although murine models might allow the identification of reduced neutrophil numbers, dissociating therapeutic differences in recruitment and clearance is more challenging but critically important. There is an important therapeutic difference between removing an unwanted neutrophil and preventing recruitment of all neutrophils to sites of potential infection.

SGK1, like AKT, is activated downstream of PI3K by PDK1/2 at similar residues (15, 25, 41), and most protein targets of SGK1 are also phosphorylated by other protein kinases such as AKT (49). However, it has previously been noted that some stress stimuli, which activated SGK1, did not result in AKT phosphorylation, showing separate rather than redundant roles for these two protein kinases (50). Although AKT activation is thought to delay neutrophil apoptosis (18), AKT can also be activated without influencing apoptosis, for example, by fMLP (19). Thus, SGK1 might in some circumstances act to transduce apoptotic signals downstream of PI3K, in parallel to AKT.

The upregulation of SGK1 by survival signals (21, 23) links to a clinically important increase in SGK1 expression seen in a number of inflammatory or fibrotic diseases during which the inflammatory response is involved, including Crohn’s disease (50) and glomerulonephritis (51). Prolonged neutrophil lifespan has been implicated in the extensive host tissue damage seen in these conditions, further underlining the therapeutic potential of SGK1 inhibition. Many current anti-inflammatory treatments block neutrophil recruitment to the site of injury but fail to remove neutrophils already there. We propose that SGK1 represents a possible target for anti-inflammatory therapeutics specifically targeting the resolution phase of inflammation while still allowing neutrophils to mount a response against infection, without the extended survival and degranulation associated with disease.

Disclosures
C.S., E.H.-G., W.Z., and S.F. are employees of GlaxoSmithKline, which has financial interest in inhibitors of SGK1 and other targets involved in inflammation resolution.
References


Supplemental Figure 1c

Supplemental Figure 1: SGK1 Protein Sequences.
There are 4 isoforms of human SGK1, differing only in their amino terminal exons. a) schematic representation of intron-exon structure. b) Protein sequence alignment showing domain structure of human SGK isoforms. c) The human and zebrafish SGK1 proteins show high sequence homology and maintenance of key domains. Protein sequence alignment between human SGK1 isoform 1 and zebrafish Sgk1.
Supplemental Figure 2: SGK1 protein levels are not determined by levels of apoptosis. Neutrophils were cultured as indicated for 8 hours. a) Relative SGK1 levels were determined by western blotting. b) GM-CSF causes neutrophil survival and Q-VD.OPh prevents almost all neutrophil death (n=3). c) Amount of SGK1 protein is not determined by amount of neutrophil apoptosis. The presence of Q-VD.OPh, while abolishing apoptosis does not affect SGK1 levels (n=3).
Supplemental Figure 3: Chemical inhibition of SGK1 causes a reduction in the amount of Mcl-1 protein in human neutrophils.

Neutrophils were cultured as indicated for 8 hours. a) Relative Mcl-1 levels were determined by western blotting. The example shown is representative of 3 independent experiments. b) GM-CSF causes neutrophil survival and GSK650394 increases the amount of neutrophil apoptosis, partially abrogating GM-CSF induced survival (n=3). c) GSK650394 treated neutrophils show decreased levels of Mcl-1 compared to the controls (n=3).
Supplemental Table 1

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Supplemental Table 1: Sequences of PCR primers

Sequences of all the primers used for PCR experiments described in this paper.