

Physiological levels of TNF α stimulation induce stochastic dynamics of NF- κ B responses in single living cells

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Summary

Nuclear factor kappa B (NF- κ B) signalling is activated by cellular stress and inflammation and regulates cytokine expression. We applied single-cell imaging to investigate dynamic responses to different doses of tumour necrosis factor alpha (TNF α). Lower doses activated fewer cells and those responding showed an increasingly variable delay in the initial NF- κ B nuclear translocation and associated I κ B α degradation. Robust 100 minute nuclear:cytoplasmic NF- κ B oscillations were observed over a wide range of TNF α concentrations. The result is supported by computational analyses, which identified a limit cycle in the system with a stable 100 minute period over a range of stimuli, and indicated no co-operativity in the pathway activation. These results suggest that a stochastic threshold controls functional all-or-nothing responses in individual cells. Deterministic and stochastic models simulated the experimentally observed activation threshold and gave rise to new predictions about the structure of the system and open the way for better mechanistic understanding of physiological TNF α activation of inflammatory responses in cells and tissues.

Key words: NF- κ B, TNF α , Live-cell imaging, Stochastic processes, Mathematical modelling, Systems biology

Introduction

Nuclear factor kappaB (NF- κ B) describes a family of dimeric transcription factors, comprising the ubiquitously expressed RelA–p50 heterodimer. NF- κ B regulates the expression of more than 300 genes involved in processes such as inflammation, immunity and cell survival (Aggarwal, 2000; Hayden and Ghosh, 2008). NF- κ B dimers are sequestered in the cytoplasm through association with members of the inhibitor kappaB (I κ B) family, preventing their nuclear accumulation. Stimulation by inflammatory mediators such as tumour necrosis factor alpha (TNF α) causes the activation of the I κ B kinase (IKK) complex, which targets NF- κ B-bound I κ B proteins for phosphorylation, leading to their ubiquitin-mediated proteasomal degradation (Zandi et al., 1998). The liberated NF- κ B translocates to the nucleus, where it regulates the expression of a plethora of target genes such as cytokines, chemokines and NF- κ B and I κ B family members that are involved in negative feedback. In the presence of sustained TNF α stimulation, NF- κ B translocates into and out of the nucleus with a period of approximately 100 minutes, and is dependent on the continual degradation and re-synthesis of I κ B proteins (Ashall et al., 2009; Friedrichsen et al., 2006; Nelson et al., 2004). These oscillations are important in temporal regulation of gene transcription, because varying the frequency of NF- κ B translocations can produce distinct gene expression profiles (Ashall et al., 2009). The concept of frequency encoding of biological output functions originated from studies of Ca²⁺ oscillations, where the strength of the response is encoded by the amplitude and frequency of changes in intracellular Ca²⁺ concentration (Berridge et al., 1998; Dolmetsch et al., 1997; Dolmetsch et al., 1998).

Cells stimulated with TNF α have the ability to secrete various cytokines, including TNF α itself. This could result in positive feedback that in turn might affect NF- κ B signalling (Coward et al., 2002; Lee et al., 2009). The strength of this positive feedback is crucial to regulate the balance between propagation of the inflammatory response and its eventual resolution. Failure to regulate this balance is often indicative of many autoimmune diseases such as chronic sepsis and arthritis. A number of studies have reported that the physiological levels of TNF α in human plasma (Nakai et al., 1999), mouse tissues (Matalka et al., 2005) and in the serum of patients surviving acute sepsis (Damas et al., 1989) are much lower than those levels used to elicit maximum responses in many experimental studies (10 ng/ml). Serum TNF α concentrations up to 5 ng/ml were found in patients who did not survive acute sepsis (Damas et al., 1989), indicating a disparity between physiological and pathogenic TNF α levels. The type 1 TNF α receptor (TNF-R1) has a very high affinity for soluble TNF α (Grell et al., 1998), suggesting that the system might detect and respond to low concentrations of TNF α . System sensitivity for low TNF α concentrations is potentially increased through interaction with TNF-R2 receptors that have the ability to effectively increase local TNF α concentration (Butera et al., 1996; Tartaglia et al., 1993). Indeed, some cell lines have been shown to be sensitive to TNF α levels as low as 8 pg/ml (Khabar et al., 1995).

One key characteristic of the response to 10 ng/ml TNF α is that individual cells show oscillations in NF- κ B cellular localisation that are out of phase between cells (Ashall et al., 2009; Nelson et al., 2004). This means that these oscillations cannot be observed at the

population level. Therefore, when probing the response to stimulation with lower doses of TNF α , it is important to consider not only the average population response, but also the possible heterogeneity between cells that would otherwise be missed. A population-level analysis suggested that at low TNF α doses, cells produce damped responses that are homogenous across the population (Cheong et al., 2006). By contrast, a theoretical study by Lipniacki and colleagues suggested that system activation at low doses might be very stochastic; however, a full NF- κ B response might be achieved even at the picomolar TNF α concentration (proposed to be due to the binding of a single TNF α trimer) (Lipniacki et al., 2007). This theoretical analysis predicted the existence of a threshold for system activation associated with an event within a TNF-R1–IKK transduction pathway.

We have investigated the contribution of single-cell dynamics to the overall population responses to TNF α and show that the heterogeneity between cells is increased at low doses of TNF α . A combination of live-cell imaging and mathematical modelling was used to assess the NF- κ B nuclear translocation kinetics in single living SK-N-AS cells following stimulation with a range of TNF α doses (1 pg/ml to 10 ng/ml). These data show that cells could still display robust 100 minute oscillations, but as the TNF α dose was lowered, the fraction of cells responding decreased and the cells showed a stochastic delay in their response. These data support the concept of a threshold for system activation, which might arise from variable inhibitor expression or from noisy upstream processes in the TNF α pathway. Deterministic and stochastic models simulated this activation threshold and allowed a better mechanistic understanding of physiological TNF α activation of inflammatory responses in cells and tissues.

Results

Dose-dependent activation of reporter gene expression by TNF α

Previous reports have shown that cells have the ability to respond to a wide range of TNF α doses (Cheong et al., 2006; Khabar et al., 1995). Therefore, we investigated the sensitivity of human SK-N-AS neuroblastoma cells to a wide range of TNF α concentrations using a luciferase reporter assay.

SK-N-AS cells were transfected with either a consensus (NF-Luc) or a specific (I κ B α -Luc) NF- κ B-inducible luciferase reporter gene. We observed a dose-dependent upregulation of expression of both reporter genes, with a maximal response at 10 ng/ml TNF α (Fig. 1A,B). Following stimulation with doses above 10 pg/ml, there was a significant increase ($P \leq 0.05$) in signal from the NF-Luc reporter construct at 4 hours compared with untreated cells (Fig. 1A). However, following stimulation with 10 pg/ml TNF α , no significant increase in signal was detectable until 6 hours after treatment (Fig. 1A). A similar response pattern was observed with the I κ B α -Luc reporter gene construct (Fig. 1B). This shows that, as previously observed in studies of other cell types (e.g. Cheong et al., 2006; Khabar et al., 1995), TNF α elicits a dose-dependent rise in NF- κ B activation.

RelA-dsRedxp translocation dynamics are dose dependent

Cell population analysis, using techniques such as EMSA (electrophoretic mobility shift assay), western blotting and RT-PCR, are informative on average responses, but mask the cellular heterogeneity inherent in the NF- κ B system (Ashall et al., 2009; Nelson et al., 2004). It is therefore not possible to discern whether

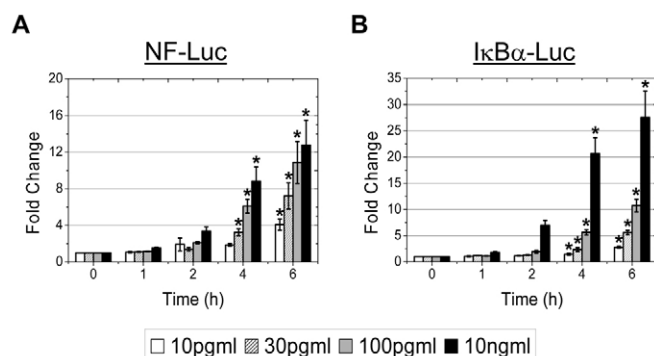


Fig. 1. Dose- and time-dependent activation of NF- κ B-inducible gene expression by TNF α . SK-N-AS cells were transiently transfected with the NF-Luc (A) or I κ B α -Luc (B) reporter constructs and were stimulated with either 10 pg/ml, 30 pg/ml, 100 pg/ml or 10 ng/ml TNF α for up to 6 hours. The luminescence signal was measured at five time points and the fold change in luminescence relative to control values was calculated. Error bars \pm s.e.m. from three replicate experiments. * $P \leq 0.05$ by ANOVA.

the reductions in signal amplitude from population assays (Fig. 1A,B) are due to a homogenous reduction in the amplitude of the response in all cells, or to heterogeneous responses from a subset of cells. Therefore, the dose-dependent response of single cells to TNF α was measured by observing the dynamics of the first nuclear translocation of fluorescently tagged RelA (RelA-dsRedxp) (Fig. 2).

Stimulation with high doses of TNF α (100 pg/ml and above) showed relatively synchronous initial nuclear translocations and gave comparatively large N:C amplitudes with a great degree of heterogeneity (Fig. 2). An intermediate dose of TNF α (30 pg/ml) reduced the synchrony in the time to the initial nuclear translocation with some translocations being highly delayed and gave a significant reduction ($P \leq 0.05$) in the N:C amplitude (Fig. 2). At doses < 30 pg/ml, a random delay in timing of the initial response was observed with many cells showing significantly delayed responses ($P \leq 0.05$) compared with cells treated with higher doses of TNF α (Fig. 2A,B). The timing of the first translocation induced by different doses of TNF α was not correlated with the intensity (protein concentration) of RelA-dsRedxp or the control EGFP (supplementary material Fig. S1, Fig. S2A-E). There was no difference in the N:C amplitude between doses of TNF α below 30 pg/ml TNF α and mock stimulation (Fig. 2C). The initial response times in cells exposed to TNF α (0, 1, 3 and 30 pg/ml) were not significantly different as a result of the very high degree of variability with no TNF α addition, only doses ≥ 100 pg/ml differed significantly from the control (Fig. 2B).

The dose of stimulus also affected the percentage of cells showing detectable TNF α -induced RelA-dsRedxp translocations (Fig. 2D). Stimulation with vehicle alone (medium) resulted in $\sim 18\%$ of cells showing an apparently significant translocation event (response) within a 300 minute period of measurement (Fig. 2D; see supplementary material Table S1A; see Materials and Methods for definition of a response). However, as the concentration of TNF α was increased, a significant rise ($P \leq 0.05$) in the number of cells responding was observed above a concentration of 1 pg/ml. At doses of 100 pg/ml and greater, 100% of cells analysed responded (Fig. 2D). Although $\sim 28\%$ of cells responded at 1 pg/ml compared with $\sim 18\%$ in the control (see supplementary material Table S1A), this was not statistically significant (Fig. 2D).

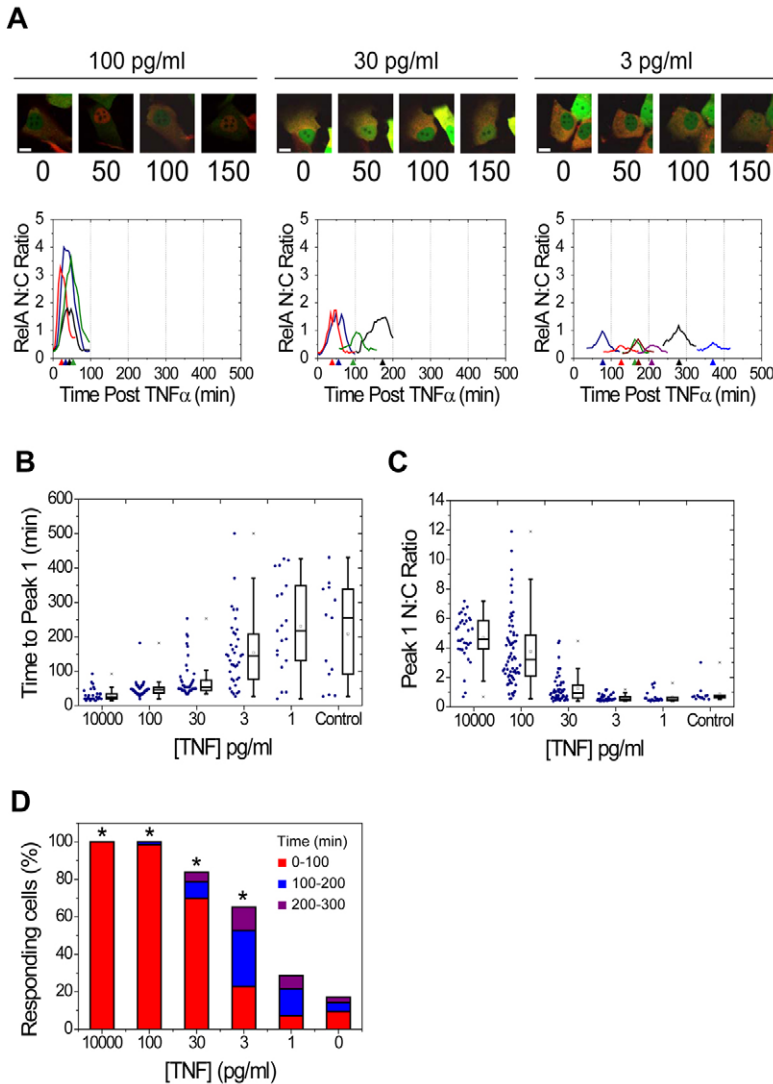


Fig. 2. Dose-dependent effects of TNF α on the amplitude and timing of the initial NF- κ B nuclear translocation in single cells. SK-N-AS cells transiently transfected with RelA-dsRedxp and an empty-EGFP plasmid were stimulated with a range of TNF α doses and imaged by time-lapse confocal microscopy. (A) Time-course showing at least four representative cells following stimulation with high (100 pg/ml), intermediate (30 pg/ml) and low (3 pg/ml) doses of TNF α . The time to the peak (maximum) of the first RelA-dsRedxp nuclear translocation is indicated with arrowheads along the x-axes. Scale bar: 10 μ m. (B) Box and whisker plot of the time to the first RelA-dsRedxp nuclear translocation (peak timing). There was no significant difference in the comparisons between 0, 1, 3 and 30 pg/ml. All other comparisons were significant ($P \leq 0.05$). (C) Box and whisker plot of the N:C amplitude following a range of TNF α doses. There was no significant difference in the comparisons between 0, 1, 3 and 30 pg/ml or between 100 pg/ml and 10 ng/ml. All other comparisons were significant ($P \leq 0.05$). Individual data points are shown to the left of each box. (D) Percentage of cells responding versus control as assessed by confocal microscopy. Colours denote the timing of the initial nuclear translocation occurring within 100 minutes (red), 100-200 minutes (blue) and 200-300 minutes (purple); * $P \leq 0.05$.

From these data (Fig. 2D), we calculated a Hill coefficient for co-operativity in dose-dependent pathway activation (see supplementary material Fig. S2F). The Hill coefficient was generated by plotting $\ln[\theta/(1-\theta)]$ against $\ln(\text{TNF}\alpha)$ for 1–100 pg/ml and estimating the slope of resulting linear trend, where θ corresponds to the percentage of responding cells (Fig. 2D) and TNF α corresponds to the dose. The data suggested a Hill coefficient of approximately 1, implying an absence of co-operativity in the mechanism of pathway activation (see supplementary material Fig. S2F).

It was shown previously that stimulation with 10 ng/ml TNF α elicited asynchronous N:C oscillations in SK-N-AS cells that maintained an average period of 100 minutes (Nelson et al., 2004). In other cell lines investigated, robust oscillations were also generated, albeit with some variation in period [e.g. shorter periods in mouse embryonic fibroblasts (Ashall et al., 2009) and rat pituitary GH3 cells (Friedrichsen et al., 2006)]. We therefore investigated whether lower doses would alter the period length or increase period variability. Surprisingly, it was found that regardless of the level of TNF α stimulation a robust 100 minute period was maintained (Fig. 3), suggesting that is a fundamental property of this system.

In summary, stimulation with high doses of TNF α resulted in synchronous initial RelA-dsRedxp translocation times with a high N:C amplitude, whereas lower doses generated reduced amplitudes and asynchronous response times. There was no difference in the amplitude or the timing of translocations at mock or low doses (0–3 pg/ml) but more cells responded to TNF α doses ≥ 3 pg/ml. Importantly, the amplitude of responses induced by very low doses was no different to that of the control, but the number of cells activated was increased, which might be functionally important in tissues.

The sustained presence of TNF α is required for NF- κ B low-dose activation

Low TNF α doses (1–3 pg/ml) generated a random initial response time that was not significantly different from the unstimulated control (Fig. 2). At these low doses, it might be necessary for receptor activation events to occur above a threshold for a response to be generated (Lipniacki et al., 2007). To test this hypothesis, cells were exposed to a short pulse (5 minutes) at a range of TNF α concentrations. Stimulation with a 10 ng/ml pulse produced a single NF- κ B nuclear translocation (Fig. 4A), as described previously (Nelson et al., 2004).

Stimulation with a range of TNF α doses (100 pg/ml, 1 ng/ml and 10 ng/ml) for a 5 minute pulse resulted in a significant ($P \leq 0.05$) dose-dependent reduction in the number of responding cells (Fig. 4B; see supplementary material Table S1B) compared with sustained stimulation (Fig. 2D). Doses of <10 ng/ml failed to activate the same proportion of cells as the equivalent dose at sustained stimulation (Fig. 2D). The most striking differences between sustained and pulsed treatment occurred after stimulation with 100 pg/ml TNF α (Fig. 4B vs Fig. 2D), where only $\sim 30\%$ of cells responded to a 5 minute pulse compared with 100% responding to sustained stimulation within 300 minutes (Fig. 4B, supplementary material Table S1B).

As the dissociation of TNF α from TNF-R1 has been reported to occur within 30 minutes and the internalisation half-time of the receptor complex has been reported to be between 10-20 minutes (Grell et al., 1998), it was considered unlikely that an initial 5 minute pulse determined responses after 50 minutes. We found that significantly fewer cells ($P \leq 0.05$) responded within 50 minutes ($12.7 \pm 11.5\%$) after a 5 minute 100 pg/ml TNF α pulse than with sustained stimulation of the same dose ($67.7 \pm 14.2\%$) (Fig. 4C vs Fig. 2A,B). There was no significant difference ($P > 0.05$) between the N:C ratio of pulsed TNF α treatments and control cells at

concentrations of <1 ng/ml (Fig. 4D). Furthermore, the method for medium replacement did not stress the cells, because there was no significant difference in the time to initial responses or the N:C ratio between a mock pulse or mock sustained stimulation (supplementary material Fig. S3A,B). In addition, estimation of a Hill coefficient from the data in Fig. 4B again suggested a lack of co-operativity in the pathway activation (supplementary material Fig. S3C).

Overall, following pulsed stimulation compared with sustained treatment with TNF α at and below 100 pg/ml the synchrony in timing of the first RelA-dsRedxp translocation was lost. Pulsed treatment also produced a N:C amplitude that was not significantly different between control and low-dose (1 or 3 pg/ml) TNF α stimulation. These data suggested that there was a threshold of activation, which required repetitive stimulation for system activation.

Evidence of a threshold of I κ B α degradation with sustained TNF α stimulation

To understand how the delay to the first translocation was regulated, and to investigate the concept of a threshold of activation, we investigated the dynamic profiles of co-transfected I κ B α -EGFP and RelA-dsRedxp in SK-N-AS cells (Fig. 5). In unstimulated conditions, we observed a basal turnover of I κ B α -EGFP with a half-life of ~ 215 minutes [which was not significantly different ($P > 0.05$) from the turnover of control EGFP protein at ~ 227

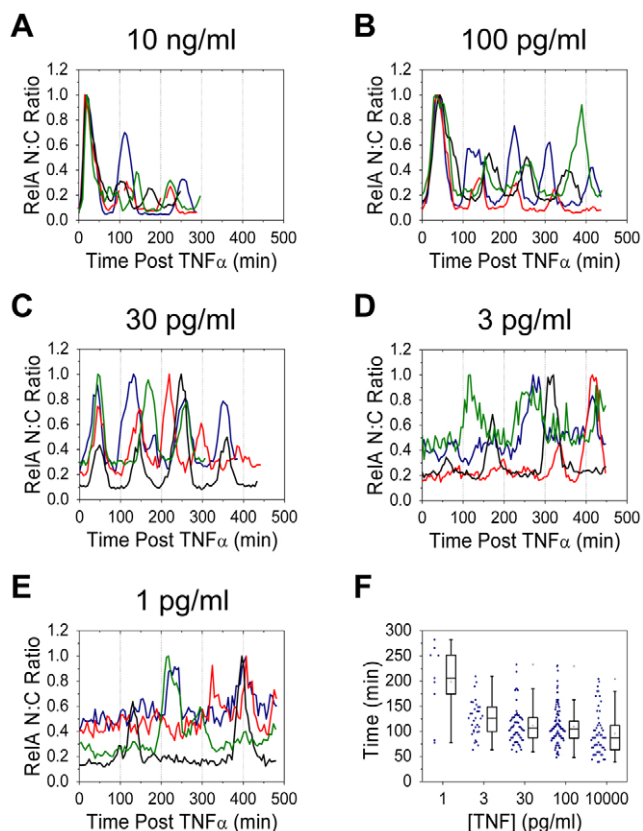


Fig. 3. Stimulation with a range of TNF α results in robust 100 minute oscillations. SK-N-AS cells transiently transfected with RelA-dsRedxp and an empty-EGFP plasmid, were stimulated with a range of TNF α concentrations. (A-E) Time-course showing four representative cells following sustained stimulation with high (10 ng/ml and 100 pg/ml), intermediate (30 pg/ml) and low (3 pg/ml and 1 pg/ml) doses of TNF α . Cell amplitudes are normalised to the maximum signal. (F) Box and whisker plots of the average peak-to-peak timing (period) of every oscillating cell per TNF α dose. Individual data points are shown to the left of each box.

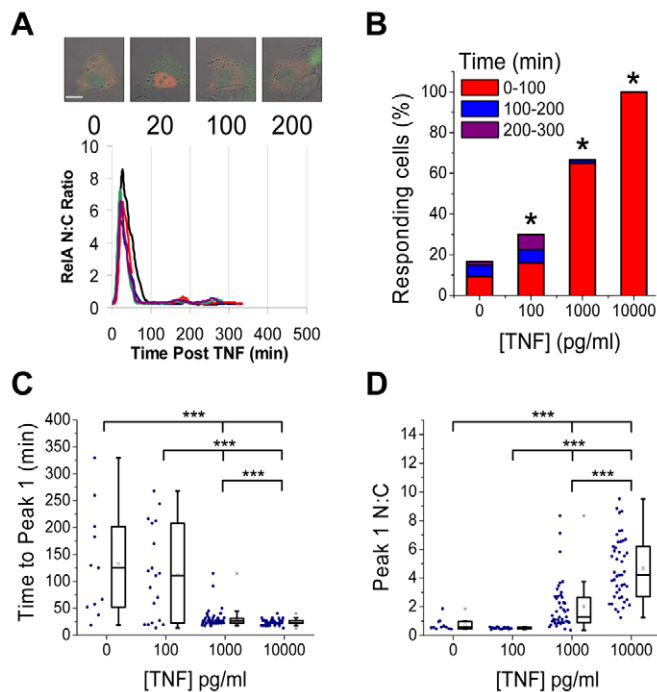


Fig. 4. Effect of TNF α pulse stimulation on amplitude and time of initial RelA-dsRedxp nuclear translocation. SK-N-AS cells transiently transfected with RelA-dsRedxp and an empty-EGFP plasmid were stimulated with a 5 minute pulse of TNF α at concentrations of 10 ng/ml, 1 ng/ml or 100 pg/ml, and imaged by time-lapse confocal microscopy. (A) Single-cell traces of five representative cells following 10 ng/ml TNF α are shown; time in minutes. Scale bar: 10 μ m. (B) The percentage of cells responding, and (C) box and whisker plots of the time to initial response and (D) the amplitude of initial response for every cell responding was plotted following analysis. Individual data points are shown to left of each box in C and D. * $P \leq 0.05$ and *** $P \leq 0.01$.

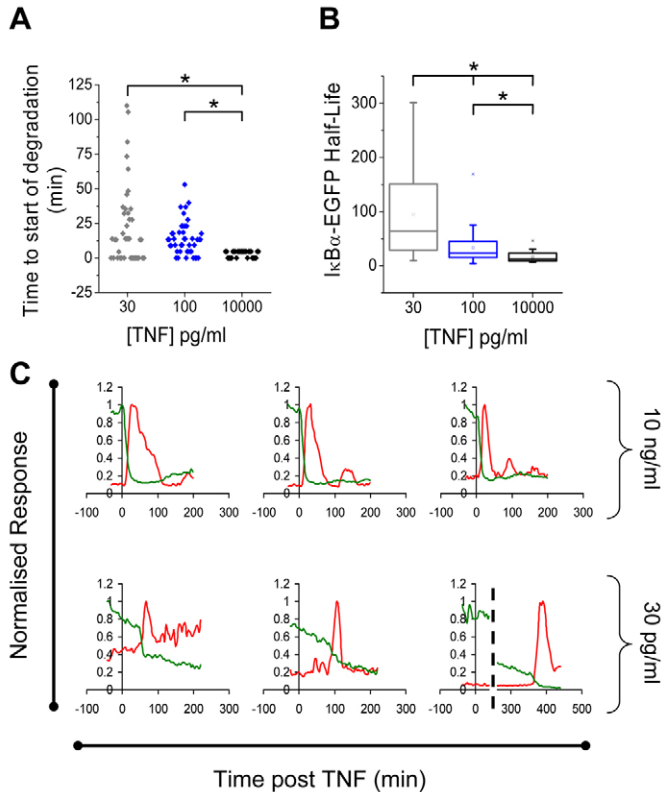


Fig. 5. The $\text{I}\kappa\text{B}\alpha$ degradation profile suggests the presence of an upstream threshold of activation. SK-N-AS cells transiently transfected with RelA-dsRedxp and $\text{I}\kappa\text{B}\alpha$ -EGFP plasmids were stimulated with 30 pg/ml, 100 pg/ml or 10 ng/ml TNF α . (A) The time to the initiation of $\text{I}\kappa\text{B}\alpha$ -EGFP degradation and (B) $\text{I}\kappa\text{B}\alpha$ -EGFP half-life at each dose were plotted. (C) Three representative single-cell traces stimulated with either 10 ng/ml (upper) or 30 pg/ml (lower) TNF α . The red line represents N:C ratio of RelA-dsRedxp and the green line represents total cellular $\text{I}\kappa\text{B}\alpha$ -EGFP fluorescent levels (average intensity per pixel, normalised to their maximum respective signal). * $P < 0.05$.

minutes]. Stimulation with 10 ng/ml induced synchronous and rapid degradation of $\text{I}\kappa\text{B}\alpha$ -EGFP with a half-life of ~16 minutes (Fig. 5). However, when cells were stimulated with lower TNF α concentrations, a different temporal profile was observed. There was a significant and apparently random time delay ($P \leq 0.05$) before $\text{I}\kappa\text{B}\alpha$ -EGFP degradation was initiated, during which $\text{I}\kappa\text{B}\alpha$ -EGFP continued to degrade with basal rate (Fig. 5A,C). Once initiated, the rate of $\text{I}\kappa\text{B}\alpha$ -EGFP degradation was significantly increased (half-lives of ~95 and ~33 minutes for 30 and 100 pg/ml, respectively) compared with the basal rate, which coincided with an onset of RelA-dsRedxp nuclear translocation. A significant difference ($P \leq 0.05$) in the $\text{I}\kappa\text{B}\alpha$ -EGFP half-life of the cell population at different doses reflected the fact that only a partial degradation was observed at low doses, which correlated with lower amplitude of N:C RelA-dsRedxp translocation (Fig. 5B,C).

To quantify possible effects of different levels of RelA-dsRedxp and $\text{I}\kappa\text{B}\alpha$ -EGFP expression, the time to the first RelA-dsRedxp response (supplementary material Fig. S4) and the RelA-dsRedxp N:C ratio (supplementary material Fig. S4) were analysed with respect to the intensity of the $\text{I}\kappa\text{B}\alpha$ -EGFP for each TNF α concentration. There was a correlation between intensity of $\text{I}\kappa\text{B}\alpha$ -EGFP and the time to the first RelA-dsRedxp response when the cells were stimulated with ≥ 100 pg/ml (supplementary material

Fig. S4A,B), as seen previously (Nelson et al., 2004). However, this correlation was lost when cells were stimulated with 30 pg/ml TNF α (supplementary material Fig. S4C). The intensity of the $\text{I}\kappa\text{B}\alpha$ -EGFP signal did not affect the amplitude of the initial response at 10 ng/ml, 100 pg/ml and 30 pg/ml TNF α (supplementary material Fig. S4).

Alterations to the existing mathematical model can simulate sustained oscillations and the delayed activation at low TNF α doses

Initially, we investigated whether existing mathematical models could capture the single-cell behaviour observed at low TNF α doses. Cheong and co-workers (Cheong et al., 2006) used ordinary differential equations based on the law of mass action, which were unable to simulate the intrinsic stochasticity of single cell responses. A theoretical model by Lipniacki and colleagues (Lipniacki et al., 2007) captured some heterogeneity of the system responses (in particular the random delay to the initial activation at low doses), by incorporating noise into the activation of TNF-R1 receptors and transcription of NF- κ B feedback genes. However, this model could not predict the maintenance of the robust 100 minute oscillations or the reduction in the N:C amplitude that was observed in these experiments (Lipniacki et al., 2007).

Previously, we described a mathematical model that was capable of reproducing the single-cell data gathered from a number of experimental conditions (such as continuous and repeat pulse stimulation) (Ashall et al., 2009). In that model, we implemented a novel IKK module, which included IKK state recycling and negative feedback from A20 that allowed the experimental observations to be replicated *in silico* (Fig. 6A). In light of the dose-response data described above, we investigated whether this model could also simulate the following observations at low doses: (1) maintenance of robust 100 minute oscillations, (2) reduction of the RelA-dsRedxp N:C amplitude, and (3) a random delay to the first response, which is associated with a biphasic $\text{I}\kappa\text{B}\alpha$ degradation profile.

We first investigated the ability of the model to maintain robust oscillations by decreasing parameter TR (Fig. 6A). (The model was developed for $TR=1$, which corresponds to 10 ng/ml TNF α .) Reduction of this parameter over successive orders of magnitude that simulated a reduction in the dose of TNF α , was unable to reproduce stable oscillations (Fig. 6A). We identified that a single modification in the IKK module (to remove the dependence of A20 inhibition on TNF α , and assume that A20 is constitutively active) produced a stable 100 minute period and a reduction in the N:C amplitude for lower TR values (Fig. 6B; supplementary material Table S2A,B). With this modification, the model still satisfactorily fitted all of the previous experimental observations (Fig. 6B). Detailed analysis indicated that whereas the original model generated a bifurcation point at a TR of 0.36 (a relatively high dose of 3.6 ng/ml) the modified IKK structure could shift the bifurcation point ten-times lower to a TR of 0.045 (Fig. 6C).

Our next aim was to explain the stochastic nature of the low-dose responses. Therefore, we developed a new stochastic model to provide a mechanistic hypothesis while making minimal biological assumptions (see Fig. 7). In particular, we have not tried to model the pathway upstream of IKK in detail because of the current lack of detailed understanding and quantitative data, but instead focused on a generic stochastic description of the activation of IKK which attempted to capture the degree of volatility caused by the incoming signals (modelled by D below). Whereas the

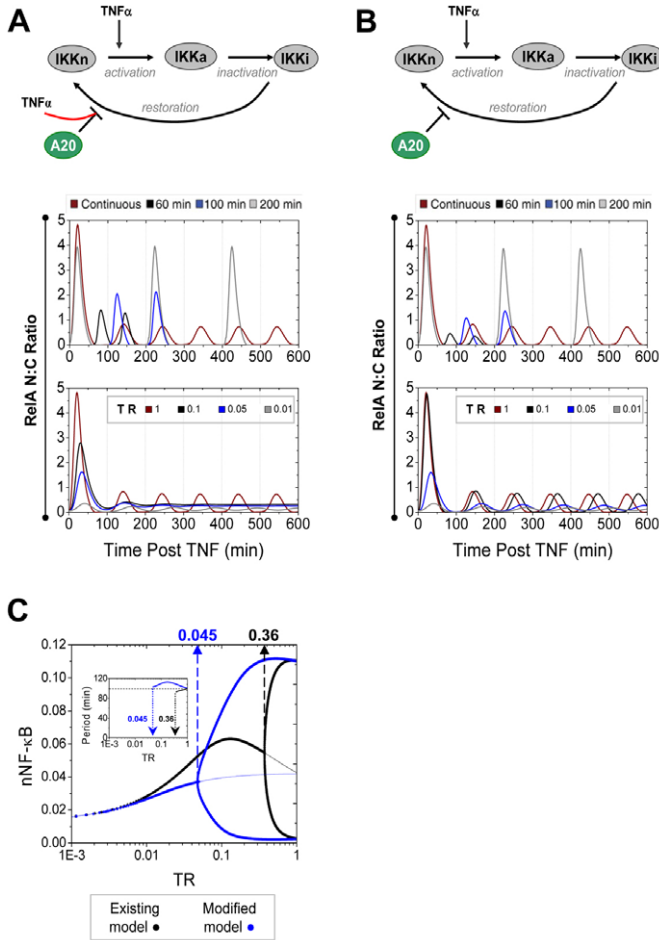


Fig. 6. A modified mathematical model can simulate sustained oscillations and the delayed activation at low TNF α doses. (A) The existing NF- κ B model (Ashall et al., 2009). The structure of the IKK module (top), model simulations for continuous and repeat-pulse TNF α treatment (5 minute stimulation at 60, 100 and 200 minutes frequency, three times) (middle) and model simulations following a decrease in TNF α dose (decrease of TR from 1 to 0.01, bottom). (B) The modified model structure of the IKK module (after removal of the TNF α -dependence of A20 inhibition, top), model simulations for continuous and repeat pulsing (as in A) TNF α treatment (middle) and model simulations following a decrease in TNF α dose (decrease of TR from 1 to 0.01, below). (C) Bifurcation analysis (with respect to TR) of the existing (black) and the modified (blue) model. Shown are nuclear NF- κ B levels in the steady state as a function of TR displaying a transition from a fixed point into a limit cycle at the bifurcation point, respectively for each model; insert presents the period of limit cycle oscillations as a function of TR .

previous model had used the single TNF α dose parameter TR , we next introduced a variable $Z(t)$, ($0 \leq Z < 1$), such that for small time steps δt :

$$Z(t + \delta t) = Z(t)(1 - \rho)\delta t + D, \quad (1)$$

where D is the effective TNF α (activation) dose and ρ is the inactivation rate, which describes the system's memory (supplementary material Table S2C). Time evolution of $Z(t)$ is represented by a first-order dynamical process representing the TNF-R1–IKK transduction pathway (Fig. 7B). For arbitrary values of ρ , we set D so that the response Z was equivalent to TR in the previous model (Fig. 6). The stochastic behaviour of the TNF α

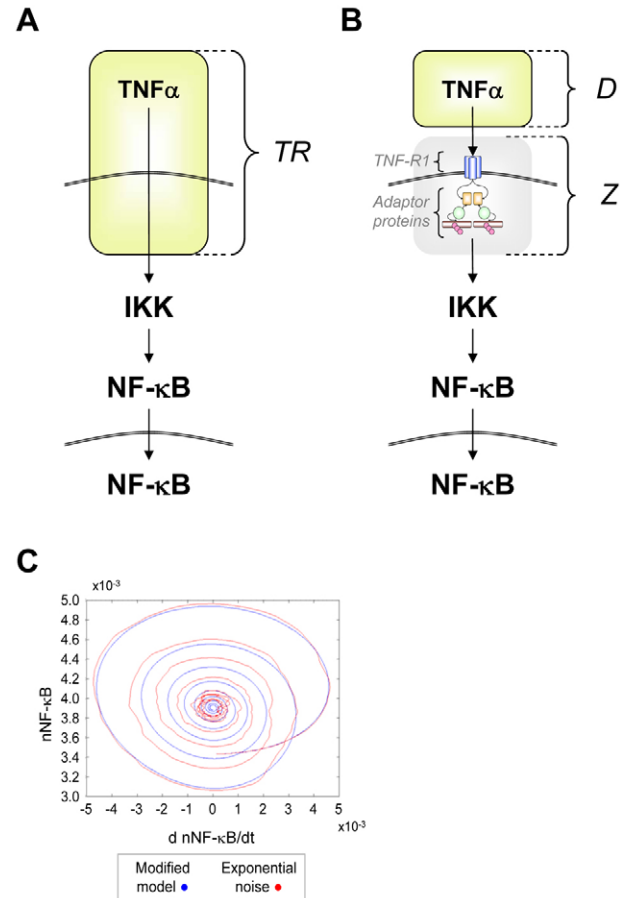


Fig. 7. Schematic representation of the steps of TNF-R1 signal transduction as encoded by the mathematical models. Noise can maintain 100 minute oscillation even below the deterministic oscillation threshold. (A) Schematic representation used in the previously described (Ashall et al., 2009) and modified model (as described in Fig. 6A and 6B, respectively). In these models, TR corresponds to a TNF α dose, which directly affects IKK activation. (B) Incorporation of the TNF-R1 transduction pathway. D represents the effective TNF α dose. Z represents the transduction process leading to IKK activation. (C) Phase plane representation [nuclear NF- κ B(t) vs its time derivative] showing how the exponential noise of the stochastic model can maintain the 100 minute oscillations even when the modified model (blue) does not. The same initial conditions were used in both models (see supplementary material Table S2C).

transduction pathway was modelled by taking D to be a random variable to be drawn from an appropriate distribution. Because such stochastic fluctuations continuously perturb the system, the model was able to induce persistent oscillations for lower TNF α doses than the equivalent deterministic model (see Fig. 7C for D randomised from exponential distribution).

The low-dose responses (Fig. 5C) were more accurately simulated when a heavy-tailed distribution for D was assumed. In Fig. 8A, single-cell RelA and I κ B α trajectories are shown. These were generated using a memory parameter value $\rho=0.07$ second $^{-1}$ and a Pareto distribution (supplementary material Table S2C) in which the probability that D is greater than any value d decreases in a power-law fashion, i.e. $\text{Pr}(D>d) = (\xi/d)^\sigma$ if $d>\xi$ ($\sigma=2$, $\xi=10^{-9}$). This exhibited stochastic NF- κ B activation and ~ 100 minute

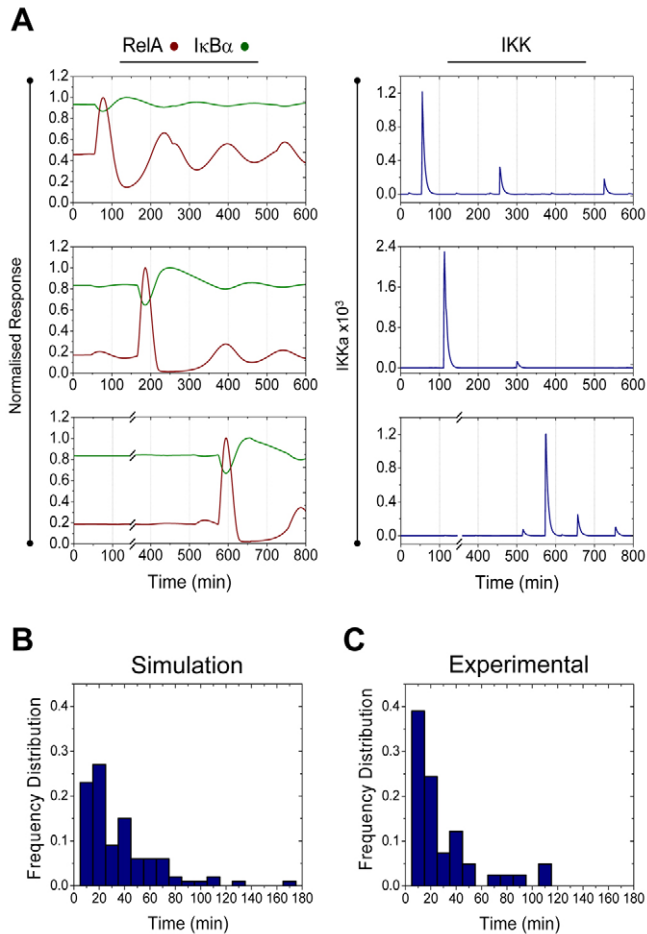


Fig. 8. A heavy-tail distribution for the effective TNF α dose can explain stochasticity of system activation at low TNF α doses. (A) Model simulations assuming noise-driven (Pareto-distributed effective dose D) kinetics of pathway activation (Eqn 1; supplementary material Table S2C). Three representative single-cell traces are shown: (left) N:C ratio of RelA (in red) and the total IκBα (in green) levels normalised to signal maximum, respectively. Corresponding active IKK trajectories are shown on the right. (B) Frequency distribution of the time to initiation of IκBα degradation assuming Pareto-distributed effective dose D (supplementary material Table S2C), calculated based on 100 simulated cells. (C) Frequency distribution of the time to initiation of IκBα-EGFP degradation following 30 pg/ml TNF α stimulation (calculated from data in Fig. 5A).

oscillations through stochastic excitation of the bifurcation point. Contrary to non-heavy-tailed distributions (e.g. exponential, supplementary material Fig. S5), a heavy-tailed Pareto distribution, in conjunction with a short-memory of signal transduction (high ρ), was able to generate dynamic trajectories of IKK levels (Fig. 8A right panel; supplementary material Table S2C) that allowed the simulation of the observed delay in single-cell activation. Based on this model it was possible to simulate initiation times of IκBα degradation that closely matched the measured distribution (Fig. 8B,C). To do this it was assumed that cells had a Pareto distribution with $\sigma=1.8$, $\xi=10^{-9}$ and included a threshold (defining system activation) that was four times the unstimulated value of active IKK.

Discussion

In this report, we used a combination of experimental and mathematical techniques to investigate the regulation of the NF-κB (RelA) transcription factor in single living SK-N-AS cells in response to physiological levels of TNF α . Previously, we and others showed that mammalian cells in response to saturating doses of TNF α (10 ng/ml) exhibited RelA oscillations with a period of approximately 100 minutes (Ashall et al., 2009; Friedrichsen et al., 2006; Nelson et al., 2004; Sung et al., 2009), and that this period could determine the pattern of downstream gene expression (Ashall et al., 2009). In the present study, we investigated whether the quantitative (timing, amplitude and oscillation frequency) characteristics of NF-κB responses were altered at low TNF α doses. Our data showed that single cells were not only able to oscillate in response to picomolar TNF α concentrations, but could also maintain a robust 100 minute period. This remarkable observation suggests that the maintenance of the 100 minute oscillation period in response to TNF α stimulation is a fundamental property of the NF-κB signalling system.

A study by Cheong and co-workers investigated NF-κB activation in response to a range of TNF α doses by using cell-population-based techniques such as gel retardation and IKK assays (Cheong et al., 2006). They showed that lowering the TNF α dose reduced the amount of nuclear NF-κB, yet maintained the same temporal profile regardless of the dose. Our data are fundamentally consistent with those of Cheong and colleagues (Cheong et al., 2006); however, our single-cell analyses demonstrate that cell populations are much more heterogeneous at lower doses of TNF α treatment. Our main observations are (1) a diminishing proportion of cells respond to decreasing doses of TNF α , (2) the N:C amplitude of the first translocation decreases with a reduction in the TNF α dose, (3) the responding cells display a stochastic delay in the time from stimulation to first observable RelA-dsRedxp nuclear translocation, and (4) the maintenance of a robust 100 minute period across all doses investigated. These data suggest that the decrease in population response observed by Cheong and colleagues was due to a combination of a smaller proportion of cells responding and a decrease in amplitude of single-cell responses, which were distributed in time.

The maintenance of robust NF-κB oscillations at a range of TNF α doses was interpreted in terms of our previously published mathematical model (Ashall et al., 2009). In that study, we identified the most generic model structure that could account for the available experimental data with fewest assumptions. Interestingly, we had previously been unable to discriminate between classes of models that invoked either TNF α -dependent or TNF α -independent inhibition via A20 feedback. With stimulation above a critical level, the previously used TNF α -dependent A20 inhibition model exhibited a stable-limit cycle with a period of approximately 100 minutes, to which the solutions converge (Fig. 6). This model could only support these stable NF-κB oscillations for high TNF α doses ($TR>0.36$; equivalent to 3.6 ng/ml TNF α). However, with a change in the structure of the IKK module (Fig. 6B) to invoke TNF α -independent A20 inhibition, the resulting model could maintain oscillations for doses approximately one-tenth of this concentration, and was still able to retain the ability to accurately simulate other stimulation conditions (Ashall et al., 2009). In both the current and modified models, the period length of the oscillations was largely independent of the stimulation level. This key observation suggests an important functional role for the conserved 100 minute NF-κB oscillations in response to widely

varying doses of TNF α . Our new experimental data also made a mechanistic prediction, by allowing us to discriminate between model structures for A20 action, which had been impossible to separate from previous data (Ashall et al., 2009). The low-dose TNF α data have therefore allowed us to make unexpected and non-intuitive predictions about the mechanism of A20 inhibition.

TNF α signalling through TNF-R1 receptors involves several steps where, following binding of trimeric TNF α to the receptor, adaptor proteins (TRAF2 and TRADD) are recruited to the receptor complex via their death domains (Hsu et al., 1996b; Hsu et al., 1995). RIP is then recruited and can ubiquitinate TRAF2 with Lys63 chains that serve as a scaffold for the IKK complex, allowing its activation (Hsu et al., 1996a; Zhang et al., 2000). Our current understanding is that in our experimental system at picomolar doses, the number of TNF α trimers available per cell is in the order of 100 molecules. This suggested that the heterogeneity of the low-dose responses could have originated from relatively small numbers of molecules at some point in the upstream signal transduction pathway, which might cause a downstream stochasticity in the number of activated IKK molecules. To analyse this mathematically, we developed a model that included stochasticity in transduction pathway leading from TNF-R1 receptor binding to IKK activation. The data suggest that the distribution of IKK activation events had to have heavy tails. Simulations with distributions with non-heavy tails (e.g. exponential distribution) did not give an appropriate activation distribution (Fig. 7C, Fig. 8; supplementary material Fig. S5), whereas heavy-tailed distributions, such as a Pareto distribution with memory, produced activation profiles that were similar to the data. It is possible that the large fluctuations seen with heavy tails are a result of processes such as receptor clustering or ligand passing from TNF-R2 to TNF-R1 (Liu et al., 2002; Tartaglia et al., 1993; Weiss et al., 1997). This model therefore describes a hypothetical and generic mechanism for generation of the observed stochastic dynamics without making unnecessary biological assumptions (Fig. 7).

Our next aim was to probe the mechanisms of NF- κ B pathway activation responsible for the apparent all-or-nothing response, which was seen under low-dose stimulations. These responses are exhibited by the biphasic profiles of I κ B α -EGFP level, which under low-dose stimulation exhibited a random but rapid transition from a low (basal; half-life, ~215 minutes) to a high degradation rate (~95 and ~33 minutes for 30 and 100 pg/ml respectively, Fig. 5C) coinciding with RelA-dsRedxp nuclear translocation. The stochasticity of the I κ B α degradation initiation time increased with decreasing TNF α dose, and therefore implied that only a fraction of cells in the population responded within a fixed period of time. The input–output relationship (Hill coefficient of approximately 1 for sustained and 5 minute pulse stimulation) between the dose and the fraction of responding cells suggested a lack of co-operativity in the signal transduction pathway. It must be noted, however, that we cannot exclude the effect of background paracrine signalling. As shown by the ~18% of apparently responding cells in the absence of external stimulation, we did not attempt to test the responses of cells in a ‘true zero stimulation’.

It has been suggested (using theoretical analysis) that the incidence and dynamics (amplitude and frequency) of NF- κ B oscillations in response to TNF α activation might be significantly altered when RelA is overexpressed through transient transfection. This hypothesis arises from modelling predictions and from single time-point immunocytochemistry analysis on fixed cells (Barken et al., 2005; Cheong et al., 2009). We have previously provided

experimental data to show that there is no correlation between the level of RelA-dsRedxp expression in transiently transfected cells (as used here) and the timing of oscillations in response to high level TNF α stimulation (Nelson et al., 2005). In the data shown in supplementary material Figs S1 and S2, we demonstrate that the level of fluorescent RelA and EGFP expression did not substantially affect the dynamics of NF- κ B translocation at lower levels of TNF α stimulation. Several recent studies have shown similar dynamics of NF- κ B oscillations when RelA is expressed at physiological (or close to physiological) levels. These include stably transfected cell lines (Ashall et al., 2009), cells infected with recombinant RelA expressing lentiviruses (Bartfeld et al., 2010; Lee et al., 2009), and MEFs from GFP-RelA knock-in mice (Sung et al., 2009). In addition, the recruitment of NF- κ B subunits to various NF- κ B-regulated promoters has been shown to be oscillatory (Ashall et al., 2009; Sun et al., 2008b) and oscillations in gene expression have also been reported in untransfected primary macrophages following stimulation with TNF α (Sun et al., 2008a). Together, these studies support the view that moderate variation in RelA expression level does not substantially affect oscillation incidence or dynamics.

During the inflammatory response, cells participate in two regulatory processes; the first concerns the fate of individual cells (commitment to apoptosis or transition through the cell cycle) in response to cytokine stimulation. The second relates to the production of NF- κ B-responsive cytokines and chemokines, which enables propagation of the inflammatory signal. These physiological processes have often been interpreted as resulting from a population of cells that display homogenous responses with dose-dependent amplitudes. Although there were some dose-dependant amplitude changes, our current analysis suggests, by contrast, that the population response arises mainly from individual cells exhibiting stochastic all-or-nothing responses with random timing. Thus, the dose-dependent control of population-level dynamics is mainly achieved by regulating the number of responding cells. This strategy might be beneficial for cell signalling systems because responding cells are fully activated, thereby avoiding potential ambiguity during crucial decision-making processes. We therefore suggest that in the NF- κ B system, robust oscillations with a defined period are a standard response to constant TNF α stimulation. However, at the local level, cells might well be exposed to fluctuating TNF α levels, which we have previously shown can force different NF- κ B translocation frequencies and result in altered gene expression (Ashall et al., 2009). We propose that the system response allows a robust and consistent (potentially all-or-nothing) gene expression profile to be generated in each responding cell. The response to lower levels of signal results in lower proportions of responding cells. This suggests that further development of models for cellular communication and propagation of inflammatory signals between cells should be a priority to allow a better understanding of the tissue-level switch between amplification and resolution of inflammation. Recent data (Paszek et al., 2010) has suggested that cell-to-cell heterogeneity is an intrinsic feature of the NF- κ B system. Therefore, the variability in response to low-dose stimulation might also be a fundamental property of the NF- κ B inflammatory response.

Materials and Methods

Plasmids

All plasmids were propagated in *E. coli* DH5 α and purified using Maxiprep kits (Qiagen). NF-Luc (pNF- κ B-Luc, Stratagene) contains five repeats of an NF- κ B-sensitive enhancer element upstream of the TATA box, controlling expression of

luciferase. pI κ B α -Luc contains nucleotides -332 to +35 of the human gene promoter driving the expression of luciferase and was a kind gift from the laboratory of Ron Hay (University of Dundee, Dundee, UK). pEGFP-N1 was from Clontech. The RelA-dsRedxp construct was previously described (Nelson et al., 2002) and contains the dsRedxp fluorescent protein (Clontech) fused to the C-terminus of RelA.

Cell culture

Human S-type neuroblastoma cells (SK-N-AS, ECACC No. 94092302) were grown in minimal essential medium (MEM) with Earle's salts (Gibco) supplemented with 10% (v/v) foetal bovine serum (FBS) (Harlan Seralab) and 1% (v/v) non-essential amino acids (NEAA) (Gibco), cultured at 37°C in 5% CO₂ and grown to 80% confluency.

Treatment of cells with TNF α

Recombinant TNF α stock (10 μ g/ml; Calbiochem) was diluted in series in serum-free MEM and was then added to the dish at the appropriate concentration. A mock stimulation was performed in control experiments using serum-free MEM. For the luciferase reporter assay, TNF α was added at the beginning of the experiment. For confocal fluorescence microscopy, TNF α was added 30 minutes after the experiment had begun to record the basal fluorescent signals.

Luciferase reporter assay

SK-N-AS cells were grown in 24-well plates (6 \times 10⁴ cells per well) and transiently transfected with the appropriate plasmid using FuGene6 (Boehringer Mannheim) at the optimised FuGene6:DNA ratio of 2:1 following manufacturer's instructions. Experiments were performed 24 hours after transfection and stimulated with the required TNF α dose for the times stated. Cells were washed once with ice-cold PBS and lysates [0.025% (w/v) dithiothreitol, 1% BSA, 1% Triton X-100, 15% glycerol, 0.1 mM EDTA, 8 mM MgCl₂, in H₂O] were prepared. Luciferase activity was measured using a PerkinElmer Envision luminometer. Experiments were performed three times and expressed as the average fold-change for each treatment \pm s.e.m.

Fluorescence microscopy

SK-N-AS cells (1.6 \times 10⁵) were seeded in 35 mm glass-bottom dishes in 3 ml medium. Cells were co-transfected after 24 hours with RelA-dsRedxp and either with pEGFP-N1 or I κ B α -EGFP, as described above. Confocal microscopy was carried out 24 hours after transfection in a humidified CO₂ incubator (37°C, 5% CO₂) using a Zeiss LSM510 on a Carl Zeiss Axiovert 200M with a 63 \times 1.4 NA DIC oil-immersion objective. dsRedxp was excited with a 543 nm green Helium Neon laser and detected through a 570 nm long-pass filter. Excitation of EGFP was carried out with a 488 nm Argon ion laser, and emitted light was reflected through a 505–550 nm band-pass filter from a 540 nm dichroic mirror. Data were captured using AutoTimeSerie Macro v1.18 (Rabut and Ellenberg, 2004). Cells were treated with the appropriate stimulation 30 minutes following the onset of time-lapse imaging and images captured every 5 minutes for at least 5 hours. Data were analysed using CellTracker (Shen et al., 2006) by exporting mean fluorescence ratios from the whole of the cytoplasmic and nuclear boundaries for each cell and expressing this as a nuclear to cytoplasmic (N:C) ratio. The average and standard deviation of the N:C ratio from the 30 minute pre-stimulation period were calculated and a threshold set which was two standard deviations above pre-stimulation average; an NF- κ B response was characterised as being a transient rise in N:C ratio with more than three data points above this threshold (Jameson et al., 2009).

Mathematical modelling

In this work, we modified our previously described two-feedback model of NF- κ B signalling (see supplementary material Table S2) (Ashall et al., 2009). Mathematical models were implemented and simulated in Matlab R2009a environment (including Statistics Toolbox). Bifurcation analysis was performed with the numerical package XPPAUT (Ermentrout, 2002).

Statistical analysis

Statistical tests between different treatments were performed by the non-parametric Kruskal–Wallis test with Bonferroni adjustment for multiple comparisons. When comparing proportions of responding cells in reporter assays, one-way ANOVA followed by a Fischer's test was used. All tests were performed at 0.05 significance level and performed using Minitab 15 (Minitab Solutions, UK) statistical software.

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