Journal of General Virology (2015), **96**, 2961–2970 DOI 10.1099/jgv.0.000243

Oxidative stress in Nipah virus-infected human small airway epithelial cells

Olivier Escaffre,[1] Hailey Halliday,[1] Viktoriya Borisevich,[1] Antonella Casola[2,3] and Barry Rockx[1,3,4]

[1]Department of Pathology, University of Texas Medical Branch, Galveston, TX, USA

[2]Department of Pediatrics, University of Texas Medical Branch, Galveston, TX, USA

[3]Department of Microbiology & Immunology, University of Texas Medical Branch, Galveston, TX, USA

[4]Department of Rare and Emerging Viral Infections and Response, Centre for Infectious Disease Control, National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands

Correspondence
Barry Rockx
barry.rockx@rivm.nl

Received 8 May 2015
Accepted 5 July 2015

Nipah virus (NiV) is a zoonotic emerging pathogen that can cause severe and often fatal respiratory disease in humans. The pathogenesis of NiV infection of the human respiratory tract remains unknown. Reactive oxygen species (ROS) produced by airway epithelial cells in response to viral infections contribute to lung injury by inducing inflammation and oxidative stress; however, the role of ROS in NiV-induced respiratory disease is unknown. To investigate whether NiV induces oxidative stress in human respiratory epithelial cells, we used oxidative stress markers and monitored antioxidant gene expression. We also used ROS scavengers to assess their role in immune response modulation. Oxidative stress was confirmed in infected cells and correlated with the reduction in antioxidant enzyme gene expression. Infected cells treated by ROS scavengers resulted in a significant decrease of the (F_2)-8-isoprostane marker, inflammatory responses and virus replication. In conclusion, ROS are induced during NiV infection in human respiratory epithelium and contribute to the inflammatory response. Understanding how oxidative stress contributes to NiV pathogenesis is crucial for therapeutic development.

INTRODUCTION

Nipah virus (NiV) is an emerging zoonotic pathogen that belongs to the genus *Henipavirus*, family *Paramyxoviridae* (Eaton *et al.*, 2005). NiV causes severe and often fatal respiratory disease and/or encephalitis in humans. NiV was first identified during an outbreak of severe encephalitis in Malaysia and Singapore in 1998–1999 (Chua *et al.*, 2000; Goh *et al.*, 2000), which involved more than 276 individuals, with a case fatality rate of 38 % (Chong *et al.*, 2002). Although the fruit bat (*Pteropus* spp.) is the natural vector (Enserink, 2000), pigs were identified as the intermediate amplifying host during this particular outbreak (Ali *et al.*, 2001; Premalatha *et al.*, 2000). Since then, outbreaks of NiV infection have occurred regularly in south-east Asia (Harit *et al.*, 2006; Hossain *et al.*, 2008; Rockx *et al.*, 2012), with the most recent cases identified in Bangladesh in February 2015 (Anonymous, 2015). The case fatality rate varies from 43 to 100 % in sporadic cases in Bangladesh/India (Anonymous, 2014; Marsh & Wang, 2012; Rockx *et al.*, 2012), and transmission in these outbreaks is associated with consumption of raw date palm sap believed to be contaminated with NiV excreted by bats (Rahman *et al.*, 2012). In addition, human-to-human transmission has been reported during more recent outbreaks (Gurley *et al.*, 2007; Harit *et al.*, 2006). Respiratory symptoms were reported more frequently during the outbreaks in Bangladesh/India (70 % of cases) compared with the outbreak in Malaysia (<30 %) (Lo & Rota, 2008) and included cough, difficulty breathing (Lo & Rota, 2008), severe pneumonia (Goh *et al.*, 2000; Paton *et al.*, 1999) and an acute respiratory distress-like syndrome (Hossain *et al.*, 2008), suggesting differences in pathogenesis between the two genetically distinct Nipah virus strains (Harcourt *et al.*, 2005). Data on histopathological lesions in the respiratory tract caused by the NiV-Bangladesh (NiV-B) strain are not available, whilst those caused by the NiV Malaysia strain are localized mainly in the small airways and include necrotizing alveolitis with haemorrhage, pulmonary oedema and aspiration pneumonia (Wong *et al.*, 2002).

However, the pathogenesis of NiV-induced airway disease in humans is still unknown, and no treatment is available to ameliorate this clinical outcome.

We reported previously that primary human respiratory epithelial cells from the small airways (SAECs) are highly permissive to NiV-B infection, resulting in a strong inflammatory and innate immune response (Escaffre *et al.*, 2013). Further analysis of our data indicated that the nuclear factor (erythroid-derived 2)-like 2 (Nrf2)-mediated oxidative stress response pathway is one of the canonical pathways that was most significantly affected during infection of SAECs (Escaffre *et al.*, 2013). Upon exposure of cells to oxidative stress, Nrf2 translocates to the nucleus and binds to the antioxidant response elements within the promoter of detoxifying/metabolizing enzymes and antioxidant enzymes, and activates their transcription. These enzymes are numerous and include glutathione *S*-transferase, NAD(P)H quinone oxidoreductase, haem oxygenase and superoxide dismutase (SOD) (Allen & Tresini, 2000; Gabbita *et al.*, 2000).

Oxidative stress has multiple origins and is the result of an accumulative effect in cells of reactive oxygen species (ROS), which are highly unstable molecules generated as byproducts of the metabolism of oxygen. The production of ROS comes from either mitochondrial function or external stressors that, when not managed by the endogenous antioxidant defences, can lead to the oxidation of cellular components like lipids, proteins and DNA (Allen & Tresini, 2000; Gabbita *et al.*, 2000). ROS are significant cell regulators, and oxidative stress contributes to the pathogenesis of acute and chronic lung inflammatory diseases such as asthma, acute respiratory distress and chronic obstructive pulmonary disease (MacNee, 2001; Morcillo *et al.*, 1999). Interestingly, influenza and respiratory syncytial virus (RSV; another member of the family *Paramyxovirus*) have also been shown to induce ROS in multiple cell types (Akaike *et al.*, 1996; Hosakote *et al.*, 2009; Yamada *et al.*, 2012). Specifically, ROS produced in RSV-infected primary human respiratory epithelial cells can modulate the immune response (Garofalo *et al.*, 2013; Hosakote *et al.*, 2009, 2012), and ROS in RSV-infected mice are associated with lung inflammation and overall clinical outcome (Castro *et al.*, 2006; Hosakote *et al.*, 2011).

We hypothesized that the deregulation of antioxidant enzyme (AOE) expression in NiV-infected respiratory epithelial cells leads to increased ROS production and oxidative stress, which results in the release of cytokines/chemokines and subsequent inflammatory cell recruitment. In order to gain further insight into the early steps of infection, here we investigated the role of oxidative stress in NiV-infected SAECs. Our results showed that NiV induces oxidative stress and modulation of AOE gene expression in SAECs, which correlate with ROS accumulation. In addition, ROS production in infected SAECs was reduced using specific ROS scavengers in a dose-dependent manner that also impacted on cytokine secretion.

RESULTS

NiV-B induces oxidative stress in human respiratory epithelial cells

To investigate whether oxidative stress is induced during NiV-B infection in respiratory epithelial cells, two oxidative stress markers, (F_2)-8-isoprostane concentration and the ratio of total glutathione to oxidized glutathione (GSH/GSSG), were monitored in mock- and NiV-B-infected SAECs. NiV-B infection of SAECs resulted in a significant increase of (F_2)-8-isoprostane levels at 24 and 48 h post-infection (p.i.) compared with control cells (Fig. 1a). In addition, there was a significant decrease in the GSH/GSSG ratio in NiV-B-infected SAECs compared with control SAECs at 6 and 24 h p.i. (Fig. 1b). No glutathione could be assessed in infected cells at 48 h p.i. Altogether, an increase of (F_2)-8-isoprostane concentration and a concomitant decrease in GSH/GSSG ratio during infection confirmed that NiV-B infection induces oxidative stress in SAECs.

NiV-B modulates AOE gene expression in SAECs

To determine whether oxidative stress in NiV-B-infected SAECs resulted from changes in AOE expression, we quantified the expression of AOE genes throughout the infection. Selection of AOEs was based on results from a previous microarray study (Escaffre *et al.*, 2013) showing that the Nrf2-mediated oxidative stress response ranked third among all canonical pathways affected by NiV-B infection in SAECs (Escaffre *et al.*, 2013). Based on this result, the gene expression of the transcription factor *Nrf2* and *SOD1*, *SOD2*, *SOD3*, catalase and glutathione *S*-transferase (*GST*)-$\alpha 4$ were assessed in NiV-B-infected SAECs.

The gene expression of transcription factor Nrf2 remained unchanged in NiV-B-infected SAECs at 6 and 48 p.i. but was downregulated at 24 h p.i. (Fig. 1c), in agreement with the microarray study. Whilst *SOD1* (data not shown) and *SOD2* gene expression levels did not follow a clear trend throughout the infection, only *SOD2* was downregulated at 48 h p.i. (Fig. 1c). *SOD3*, *GST*-$\alpha 4$ and catalase gene expression levels were also significantly downregulated at 24 and 48 h p.i. compared with the control (Fig. 1c). These data showed that *Nrf2*, *SOD2–3*, *GST*-$\alpha 4$ and catalase gene expression are downregulated late in NiV-B-infected SAECs, which probably results in high levels of cellular free radical species such as superoxide anions and hydroxyl radicals, and no or limited hydrogen peroxide cellular detoxification, resulting in oxidative stress.

NiV-B-induced oxidative stress in SAECs is reduced by treatment with ROS scavengers

In order to determine whether oxidative stress in NiV-B-infected SAECs can be prevented, SAECs were treated

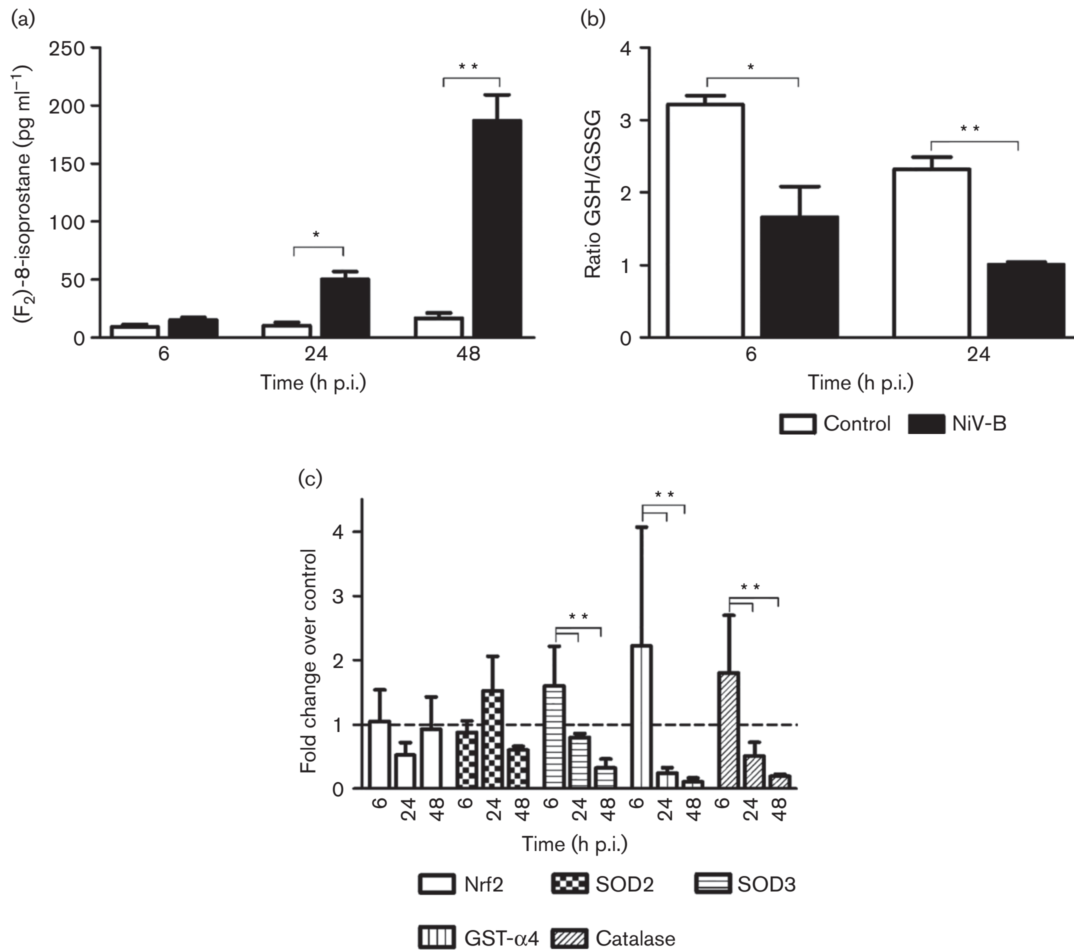

Fig. 1. NiV-B induces oxidative stress in SAEC and modifies antioxidant gene expression. (a, b) (F_2)-8-isoprostane quantification in SAEC culture supernatants (a) and GSH/GSSG ratio assessment in SAECs (b) were performed as described in Methods. *$P<0.05$, **$P<0.01$, Student's *t*-test. (c) qPCR analysis of SOD2, SOD3, catalase, GST-α4 and transcription factor Nrf2 gene expression in NiV-B-infected SAECs compared with non-infected SAECs. The horizontal dashed line represents the threshold at which there was no gene expression change. Anything above or below this threshold indicates upregulation or downregulation, respectively, of a particular gene in infected cells compared with control cells. All results are expressed as the mean ± SD of three biological samples. **$P<0.01$, Student's *t*-test.

with compounds known to have direct or indirect antioxidant effect. Two ROS scavengers, pyrrolidine dithiocarbamate (PDTC) and butylated hydroxyanisole (BHA), were tested as well as the ROS xanthine oxidase enzyme inhibitor febuxostat (Feb). Feb was significantly less efficient in reducing oxidative stress compared with the other two compounds (Fig. 2a). Indeed, SAEC treatment with PDTC and BHA, but not with Feb, drastically lowered the difference in (F_2)-8-isoprostane levels at 48 h p.i. between uninfected and infected cells. Interestingly, none of the drug compounds tested reduced syncytium formation or delayed the cytopathic effects (data not shown). The reduction in (F_2)-8-isoprostane levels in NiV-B infection by treatment with PDTC and BHA was dose dependent (Fig. 2b, c). Overall, BHA treatment resulted in a more potent reduction in oxidative stress compared with PDCT. These data showed that PDTC and BHA treatment of SAECs can prevent oxidative stress during NiV-B infection.

BHA reduces NiV-B replication in SAECs

As the level of oxidative stress induced during NiV-B infection of SAECs was significantly modulated by PDTC and BHA, we investigated whether these compounds also had antiviral properties (Fig. 3). Regardless of the concentration used, the treatment of SAECs with PDTC did not significantly affect the virus titre at any time point when compared with the virus titre in non-treated SAECs (Fig. 3a). Pre-treatment of SAECs with 100 μM BHA significantly reduced the virus titre by 2 $\log_{10}$ at 24 h p.i. and by 1 $\log_{10}$ at 48 h p.i. compared with the virus titres in

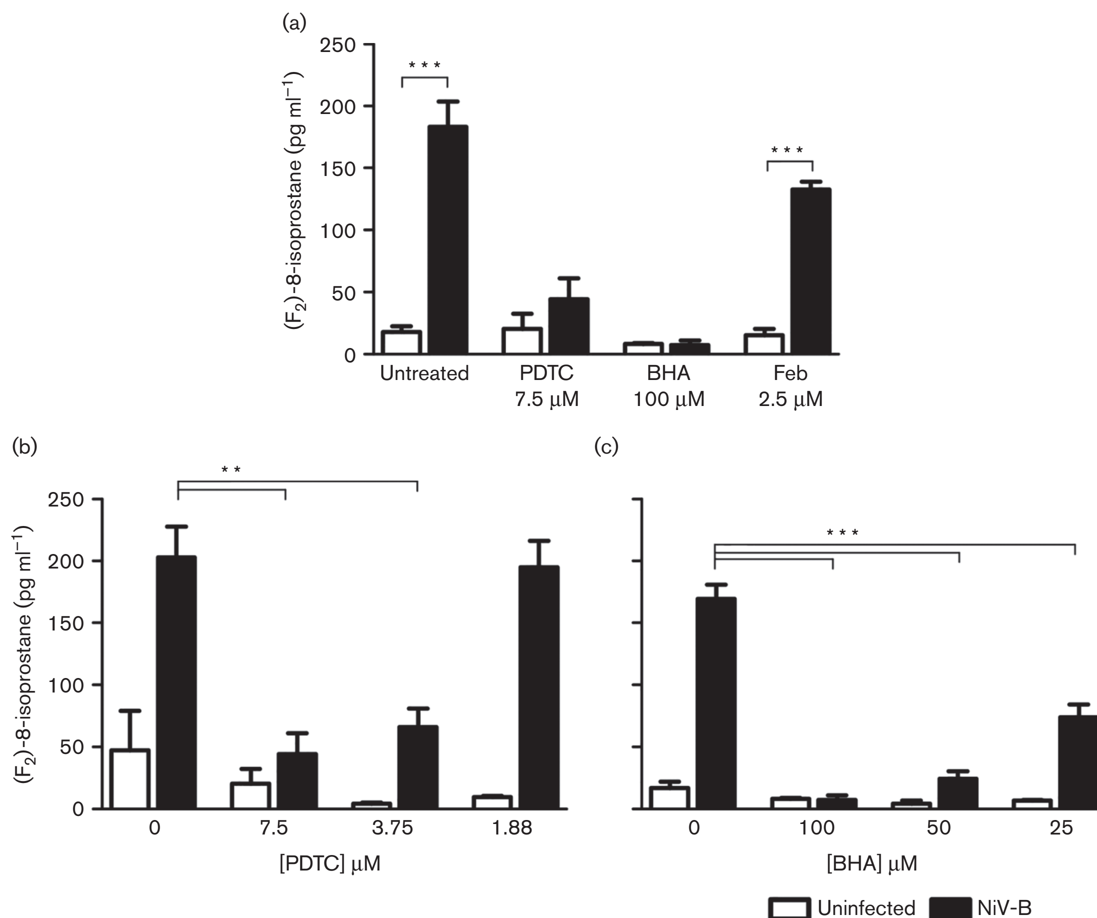

Fig. 2. Oxidative stress in NiV-B-infected SAECs can be lowered using ROS scavengers. (a) Levels of lipid peroxidation product (F_2)-8-isoprostane quantified at the 48 h time point in supernatants of SAECs undergoing different drug treatments. The assay was performed with biological triplicates using 7.5 μM PDTC, 100 μM BHA or 2.5 μM Feb. ***$P<0.001$ (Student's *t*-test). (b, c) Levels of lipid peroxidation product (F_2)-8-isoprostane quantified at the 48 h time point in supernatants of SAECs undergoing twofold dilution treatments with PDTC (b) and BHA (c). **$P<0.01$ or ***$P<0.001$ corresponds to a significant difference of (F_2)-8-isoprostane level between infected cells non-pre-treated or pre-treated with various PDTC (b) or BHA (c) concentrations (ANOVA and Bonferroni's multiple comparison test).

non-pre-treated SAECs (Fig. 3b). However, this reduction in virus titre was not observed at lower concentrations of BHA. These data showed that BHA not only has an antioxidant effect but also can reduce virus replication.

PDTC and BHA affect cytokine production in NiV-B-infected SAECs

In order to determine the effect of ROS modulation on the host response, a subset of cytokines/chemokines was quantified. Selection of the cytokines was based on results from previous studies (Escaffre *et al.*, 2013). Among a panel of 15 human cytokines/chemokines, the expression levels of four cytokines [granulocyte colony-stimulating factor (G-CSF), granulocyte–macrophage colony-stimulating factor (GM-CSF), IL-6 and CXCL10] were reduced by the two lower concentrations of PDTC in infected SAECs at 48 h p.i. (Fig. 4). Specifically, G-CSF, GM-CSF, IL-6 and CXCL10 concentrations were all significantly lower in PDTC-treated compared with non-treated infected SAECs. The concentration of IL-6 was also significantly decreased in 7.5 μM PDTC-treated compared with non-treated infected SAECs, whereas the GM-CSF level was significantly increased under the same experimental conditions. However, its level relative to uninfected controls was lower in treated versus untreated cells.

Only GM-CSF and IL-6 cytokine secretion levels were reduced by BHA treatment (Fig. 5a, b). In particular, the levels of GM-CSF and IL-6 were significantly lowered in 100 μM BHA-treated compared with non-treated infected

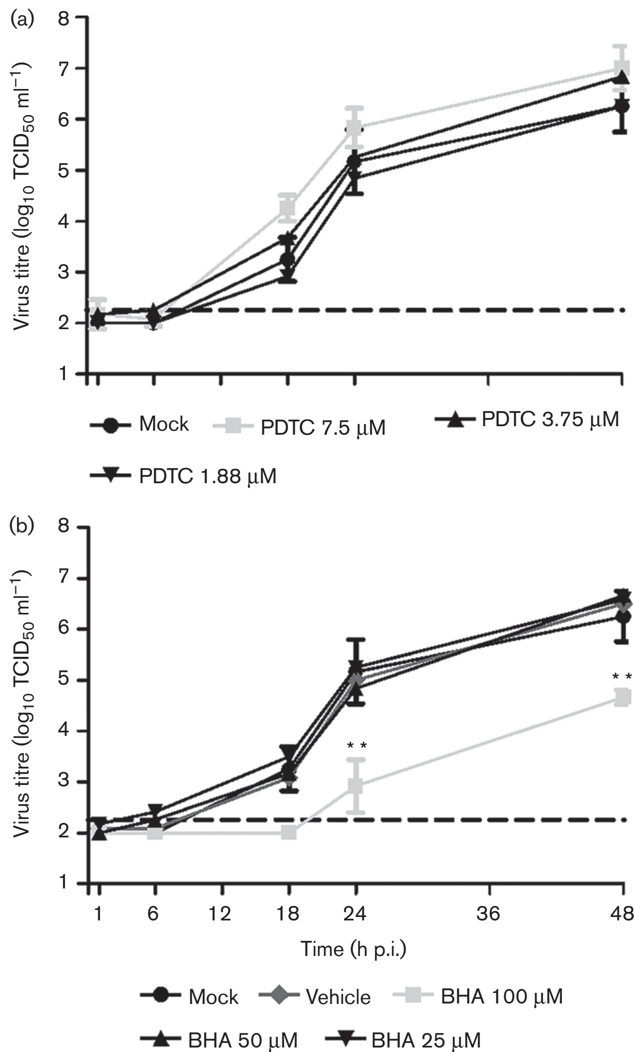

Fig. 3. Effect of antioxidant pre-treatment of SAECs on NiV-B replication. Kinetics of virus replication in SAECs treated with PDTC (a) or BHA (b) starting 1 h prior to infection. Results are expressed as the mean $\pm$ SD of three biological repetitions. The horizontal dashed line corresponds to the detection limit. $^{**}P<0.01$ corresponds to a significant difference in virus replication level between non-pre-treated and pre-treated infected cells, with the highest PDTC or BHA concentration (ANOVA and Bonferroni's multiple comparison test).

SAECs. These data showed that PDTC and BHA are able to reduce the secretion of several inflammatory cytokines including G-CSF, GM-CSF, IL-6 and CXCL-10 in NiV-B-infected SAECs.

DISCUSSION

NiV is a deadly emerging zoonotic virus that can cause severe and acute respiratory disease and/or encephalitis in humans. To date, studies have mostly focused on the neurological aspects of the disease, whilst infection of the human respiratory tract remains poorly investigated. We recently showed that NiV efficiently infects and replicates in human respiratory epithelial cells, resulting in a strong inflammatory response (Escaffre *et al.*, 2013; Valbuena *et al.*, 2014). Here, we specifically report Nrf2-mediated oxidative stress response canonical pathway deregulation and oxidative stress in NiV-B-infected SAECs, and we investigated whether an antioxidant treatment could both reduce oxidative stress and modulate the innate immune response that contributes to NiV pathogenesis in the human respiratory tract. In the current study, NiV-B was used, as it has been associated with increased respiratory disease and is the only NiV strain known to currently circulate and cause outbreaks in Bangladesh/India (Anonymous, 2014; Lo & Rota, 2008).

ROS that encompass oxidants and free radical species are generated by molecular oxygen reduction, deregulated mitochondria and cell membrane-associated specific enzymes, and by other mechanisms. The ROS level regulates the Nrf2-mediated oxidative stress response pathway. The transcription factor Nrf2, when not sequestered by its inhibitor Kelch-like ECH-associated protein 1 (KEAP1) in the cytoplasm, translocates to the nucleus and activates AOE genes by binding to their antioxidant response elements (Allen & Tresini, 2000; Gabbita *et al.*, 2000). The antioxidants can then detoxify the cell from ROS and prevent new ROS formation.

Both (F_2)-8-isoprostane levels and total versus oxidized glutathione ratios have been used previously as markers of oxidative stress (Hosakote *et al.*, 2009). Using these markers, we also demonstrated here that oxidative stress occurs in NiV-B-infected SAECs. Similar to what was observed during RSV-induced oxidative stress in SAECs (Hosakote *et al.*, 2009), NiV-B triggered a downregulation of the *Nrf2* gene and affected AOE gene expression involved in ROS neutralization and detoxification. The increase in oxidized glutathione in NiV-B-infected SAECs starting at 6 h p.i. suggested an early increase in free radical species, similar to RSV-induced oxidative stress in SAECs (Hosakote *et al.*, 2009). The level of gene expression of *GST-α4*, which participates in ROS detoxification, decreased over time in NiV-B-infected SAECs; this has also been described for another member of GST with a similar function in RSV-infected A549 cells (Hosakote *et al.*, 2009). Finally, ROS levels at a late stage of infection in NiV-B-infected SAECs were then probably even more increased due to lower gene expression of *SOD2/SOD3* and catalase, which are responsible for free radical species dismutation and oxidant catalysis, respectively. Again, these phenomena were also observed in RSV- and influenza virus-induced oxidative stress in respiratory epithelial cells (Hosakote *et al.*, 2009; Pyo *et al.*, 2014). Surprisingly, *SOD2* gene expression was downregulated at a late stage of NiV-B infection in SAECs whilst it was strongly upregulated by RSV (Hosakote *et al.*, 2009). *SOD2* upregulation in RSV-infected SAECs was attributed to RSV-induced activation

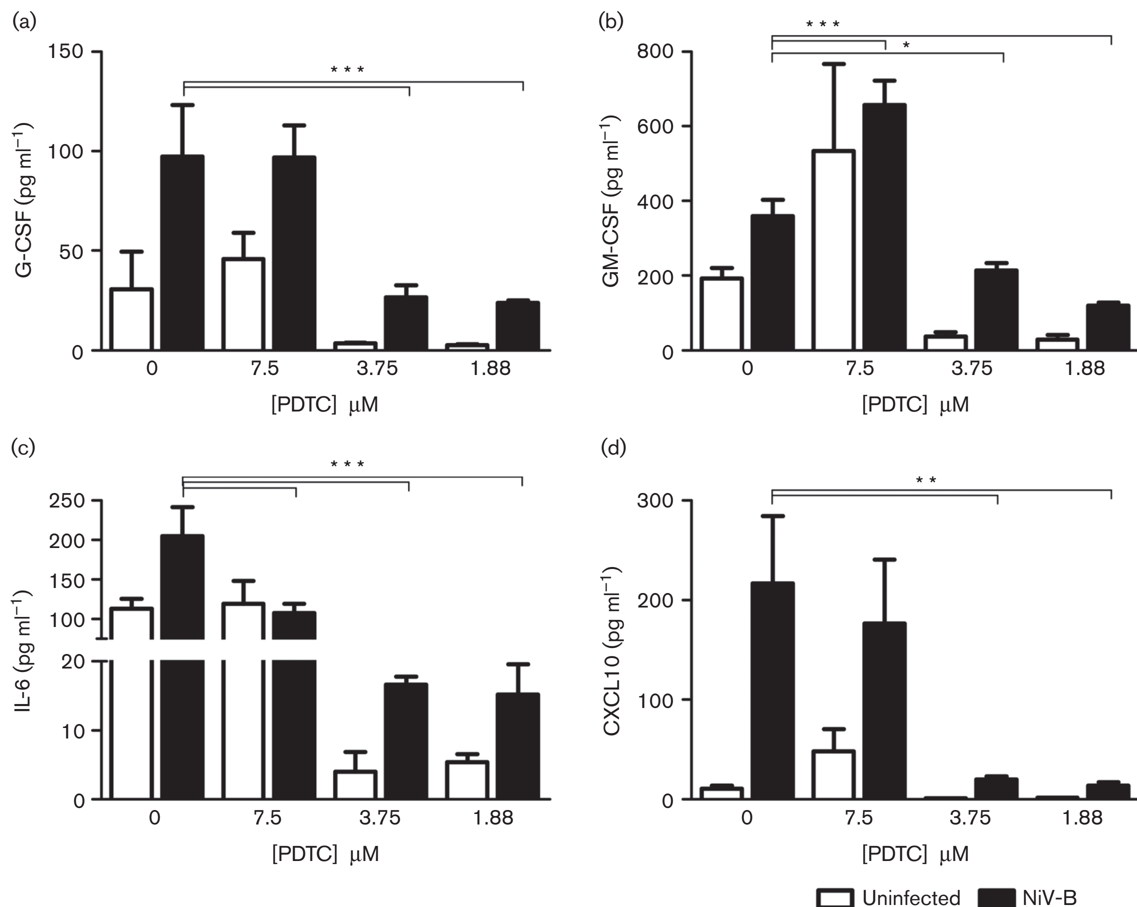

Fig. 4. Quantification of cytokines/chemokines secreted by PDTC-treated SAECs. Results shown the amount of G-CSF (a), GM-CSF (b), IL-6 (c) and CXCL10 (d) secreted by PDTC-treated SAECs at 48 h p.i. Results are expressed as the mean ± SD of three biological repetitions. *$P<0.05$, **$P<0.01$ and ***$P<0.001$ (ANOVA and Bonferroni's multiple comparison test).

of the NF-κB transcription factor (Garofalo *et al.*, 1996), which can bind to the *SOD2* gene promoter (Kinnula & Crapo, 2003). This was also reported in influenza virus-infected A549 cells (Knobil *et al.*, 1998) and suggests that regulation of the *SOD2* gene in respiratory epithelial cells is modulated differently between NiV-B and RSV or influenza virus. Altogether, these results suggest that, similar to RSV, oxidative stress in NiV-B-infected SAECs is at least in part due to deregulation of the Nrf2-mediated oxidative stress response pathway. However, the exact mechanism by which NiV-B and RSV directly interact with this pathway remains unknown.

Antioxidants have been used previously in different models of respiratory infections to control ROS levels (Castro *et al.*, 2006; Knobil *et al.*, 1998; Uchide *et al.*, 2002). The mechanisms by which PDTC and BHA modulate ROS levels are different from one another; PDTC has a similar effect to the cellular antioxidant glutathione (Uchide & Toyoda, 2011), whilst BHA prevents lipid oxidation (Aksu & Kaya, 2005; Casola *et al.*, 2001; Kashanian & Ezzati Nazhad Dolatabadi, 2009) and indirectly induces activation of Nrf2 (Kong *et al.*, 2001; Yuan *et al.*, 2006). Here, our data showed that PDTC and BHA were able to control oxidative stress in NiV-B-infected SAECs in a dose-dependent manner.

In addition, PDTC blocks influenza virus proliferation by recruiting intracellular copper and zinc ions (Kim *et al.*, 1999), which inhibit the viral polymerase activity (Oxford & Perrin, 1974). Here, PDTC did not affect NiV-B replication in SAECs but it is unknown whether NiV-B viral polymerase is sensitive to these ions or if the lack of effect on replication is due to the PDTC concentration used in this study. Conversely, BHA reduced NiV-B replication in SAECs when used at high concentration. Consistent with our data, BHA protects Vero cells from vesicular stomatitis virus-induced oxidative stress and lowered virus replication

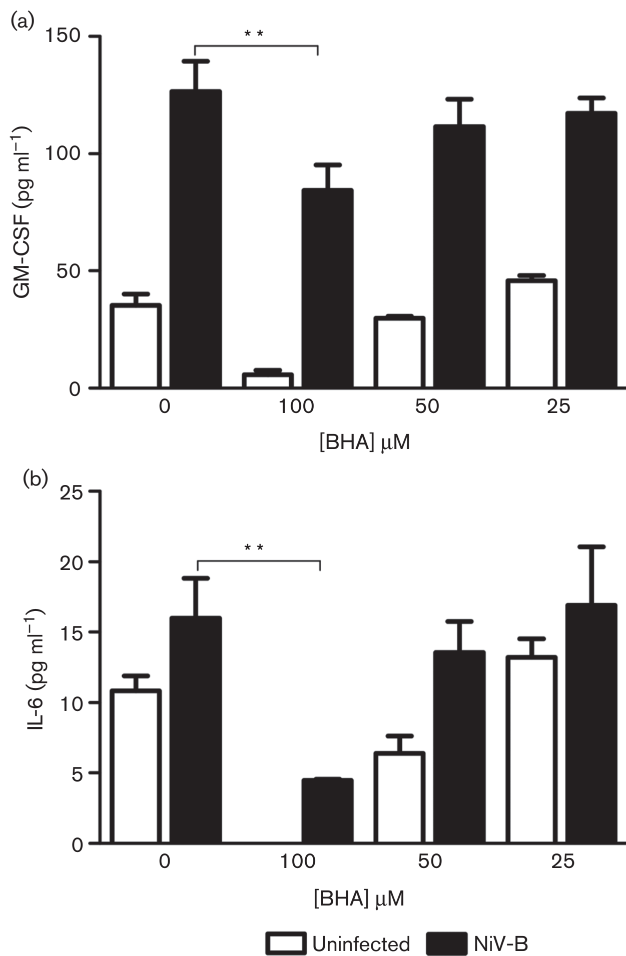

Fig. 5. Quantification of cytokines/chemokines secreted by BHA-treated SAECs. Results shown the amount of G-CSF (a) and IL-6 (b) secreted by BHA-treated SAECs at 48 h p.i. Results are expressed as the mean±SD of three biological repetitions. *$P<0.01$ and ***$P<0.001$ (ANOVA and Bonferroni's multiple comparison test).

(Riva *et al.*, 2006), but the mechanism by which BHA interferes with replication of viruses remains unknown.

PDTC and BHA treatment of NiV-B-infected SAECs significantly decreased the secretion level of cytokines such as G-CSF, GM-CSF, IL-6 and CXCL10. The mechanism of action for PDTC is unknown but, when used at a high concentration, appears to increase the baseline cytokine production possibly masking the effect. Consistent with our data, IL-6 gene expression is prevented by PDTC treatment of influenza virus-infected A549 cells (Uchide & Toyoda, 2011) and the level of IL-6 and GM-CSF is also significantly lowered by BHA treatment of RSV-infected mice, as is the migration of neutrophils into the lung (Castro *et al.*, 2006). Interestingly, CXCL10 and IL-6 gene upregulation correlates with pulmonary inflammatory cell infiltrates in NiV-infected hamsters (Rockx *et al.*, 2011). NiV-infected human lung grafts exhibiting syncytia formation in the epithelium also have increased secretion levels of G-CSF, GM-CSF, IL-6 and CXCL10 among other cytokines (Valbuena *et al.*, 2014). Therefore, these data suggest that PDTC and BHA attenuate part of the inflammatory response in NiV-B-infected SAECs and that both PDTC and BHA could reduce NiV-B-induced acute lung injury.

In conclusion, our data indicate that NiV-B infection of SAECs deregulates the Nrf2-mediated oxidative stress response pathway, which lowers AOE production, contributing to increased intracellular ROS levels and oxidative stress. Antioxidants such as PDTC and BHA decreased oxidative stress and displayed an antiviral effect for the latter. This study also demonstrated that NiV-B-induced oxidative stress contributes to an inflammatory response in SAECs and suggests that oxidative stress may play an important role in NiV-B pathogenesis by causing inflammation-mediated oxidative stress injury in the human respiratory tract. Understanding how alterations in the cytoprotective defences against oxidative stress, in the context of NiV-B infection, can contribute to respiratory disease is critical to help us identify molecular targets for future therapeutic development.

METHODS

Virus and cells. NiV-B was kindly provided by the Special Pathogens Branch (Centers for Disease Control and Prevention, GA, USA). NiV-B was isolated from a throat swab of a patient exhibiting a respiratory involvement during the 2004 outbreak in Rajbari district, Bangladesh. The virus was propagated in Vero cells (CCL-81; American Type Culture Collection) as described previously (Escaffre *et al.*, 2013).

SAECs from the distal airspace were obtained with the Clonetics Normal Human Small Airway Epithelial cell system (CC-2547; Clonetics). Monolayers of non-differentiated SAECs were cultured in a 150 cm^3 flask for 8 days (37 °C, 5 % CO_2) with Small Airway Epithelial Cell Basal Medium supplemented with growth factors (SAGM BulletKit; Clonetics). SAECs were seeded in 12-well plates at 0.4×10^6 cells per well (each condition was performed in triplicate) the day prior to infection. Six hours prior to infection, the medium was removed and replaced with basal medium, not supplemented with growth factors, as described previously (Hosakote *et al.*, 2009). All SAEC infections were performed at an m.o.i. of 1 for 1 h at 37 °C. Cells were then rinsed three times with 1× PBS and appropriate medium was added (basal medium without growth factors).

Viruses were titrated on Vero cells in 96-well plates using 10-fold virus dilutions in triplicate as described previously (Escaffre *et al.*, 2013). Virus titre was expressed as $TCID_{50}$ ml^{-1} using the method of Reed & Muench (1938). All infectious work was performed in a class II biological safety cabinet in a Biosafety Level 4 Laboratory at the Galveston National Laboratory, University of Texas Medical Branch.

Measurement of lipid peroxidation products. Measurement of the lipid peroxidation marker (F_2)-8-isoprostane in cell culture supernatants (experiment performed with biological triplicates) was performed using a competitive enzyme immunoassay (Cayman Chemical), as described previously (Hosakote *et al.*, 2009).

Determination of glutathione. Total or oxidized glutathione concentrations in the cell lysates (experiment performed with biological triplicates) were measured using a glutathione colorimetric assay (Cayman Chemical), as described previously (Hosakote *et al.*, 2009). Briefly, total cell lysates were deproteinated by adding an equal volume of metaphosphoric acid reagent (0.1 g ml^{-1} in HPLC-grade water). After incubation at room temperature for 5 min and centrifugation at 2000 ***g*** for 2 min, the supernatant was collected, and after addition of 4 M triethanolamine (TEAM) reagent, it was used for total glutathione (GSH) measurement. For oxidized glutathione (GSSG) measurement, 2-vinylpyridine (1 M) was added to the sample solution with TEAM reagent, incubated at room temperature for 1 h and then assayed for GSSG, according to the manufacturer's instructions.

qPCR. Total cellular RNA from SAECs was extracted (experiment performed with biological triplicates) using TRIzol reagent (Invitrogen), following the manufacturer's recommendations. Quantitative reverse transcription (RT)-PCR assays were performed using TaqMan gene expression assays (Life Technologies), which provide a 20 × mix of a single TaqMan MGB probe and two unlabelled oligonucleotide primers to specifically assess *SOD1*, *SOD2*, *SOD3*, catalase, *GST-α4* or *Nrf2* gene expression. In addition, the 18S rRNA gene (VIC dye-labelled probe) TaqMan assay reagent was used as an endogenous control (Life Technologies). Single-plex one-step RT-PCRs were performed using the Quantifast Probe RT-PCR kit (Qiagen). The cycling parameters for one-step RT-PCR were the following: reverse transcription 50 °C for 10 min, followed by 45 cycles of activation 95 °C for 5 min, denaturation 95 °C for 10 s and annealing/extension 60 °C for 30 s on a Bio-Rad CFX96. Duplicate threshold cycle (C_T) values were analysed using the comparative C_T ($\Delta\Delta C_T$) method. The amount of target gene expression level ($2^{-\Delta\Delta C_T}$) was calculated by normalizing to the endogenous reference (18S rRNA gene) sample.

Compound preparation and viability test. The two ROS scavengers PDTC and BHA (Sigma-Aldrich) were resuspended in sterile PBS and absolute ethanol, respectively, and aliquoted prior to storage at −80 °C. Feb (Cayman Chemicals), a ROS xanthine oxidase enzyme inhibitor, was resuspended in absolute ethanol, aliquoted and stored at −80 °C. PDTC was further diluted to 7.5, 3.75 and 1.88 μM in SAEC basal medium prior to use. Similarly, BHA was diluted to 100, 50 and 25 μM. Feb was diluted to 2.5, 1.25 and 0.63 μM. The concentration at which each compound was not cytotoxic for SAECs was evaluated by first seeding 2×10^6 SAECs per 96-well plate, treating each row of cells of the plates with twofold serial dilutions of either PDTC, BHA, Feb or SAEC basal medium for 48 h (experiment performed in quadruplicate) and then using a cell growth determination MTT-based kit (Sigma-Aldrich) following the manufacturer's instructions. From these results, PDTC, BHA and Feb were used at a maximum concentration of 7.5, 100 and 2.5 μM, respectively.

Antioxidant treatment. SAEC culture and seeding in 12-well plates was performed as described above. Starting 1 h prior to infection, the basal medium was replaced by basal medium supplemented with different concentrations of either PDTC or BHA. All SAEC infections were performed as described above. Cells were then rinsed three times with 1 × PBS, and fresh basal medium supplemented with different concentrations of either PDTC or BHA was added (performed in triplicate).

Milliplex analysis. Cytokine/chemokine concentrations in the supernatant of henipavirus-infected SAECs were determined using a Milliplex Human Cytokine 15 Plex Immunoassay custom kit (Millipore). Prior to analysis, samples (experiment performed with biological triplicates) were inactivated on dry ice by gamma irradiation (5 Mrad). The assay was performed according to the manufacturer's instructions. The human cytokine standards were prepared using the SAEC basal medium. The concentrations of 15 cytokines [G-CSF, GM-CSF, IFN-α2, IFN-γ, IL-1α, IL-1β, IL-6, IL-8, IL-1RA, CXCL10, eotaxin, monocyte chemotactic protein-1, TNF-α, fractalkine (CX3CL1) and vascular endothelial growth factor A] were quantified.

Statistical analyses. Comparisons of virus replication levels and cytokine/chemokine secretion levels were subjected to a repeated measure one-way ANOVA test. When the ANOVAs revealed a significant main effect, a post-hoc test such as Bonferroni's multiple comparison test was used to determine whether treatment means were significantly different from one another. Comparison of GSH/GSSG ratios and (F_2)-8-isoprostane levels was performed using a two-tailed Student's *t*-test. All data are presented in the figures as means ± SD (**P*<0.05, ***P*<0.01, ****P*<0.001).

ACKNOWLEDGEMENTS

This work was supported by the University of Texas Medical Branch startup funds (to B. R.), National Institutes of Health (1R21AI111042-01 to B. R. and P01AI07924602 to A. C.), and a UTMB Center for Tropical Diseases Postdoctoral Fellowship (to O. E.). The authors would like to thank Drs Alexander Freiberg and Gustavo Valbuena for helpful discussions.

REFERENCES

Akaike, T., Noguchi, Y., Ijiri, S., Setoguchi, K., Suga, M., Zheng, Y. M., Dietzschold, B. & Maeda, H. (1996). Pathogenesis of influenza virus-induced pneumonia: involvement of both nitric oxide and oxygen radicals. *Proc Natl Acad Sci U S A* **93**, 2448–2453.

Aksu, M. I. & Kaya, M. (2005). The effect of α-tocopherol and butylated hydroxyanisole on the colour properties and lipid oxidation of kavurma, a cooked meat product. *Meat Sci* **71**, 277–283.

Ali, R., Mounts, A. W., Parashar, U. D., Sahani, M., Lye, M. S., Isa, M. M., Balathevan, K., Arif, M. T. & Ksiazek, T. G. (2001). Nipah virus among military personnel involved in pig culling during an outbreak of encephalitis in Malaysia, 1998-1999. *Emerg Infect Dis* **7**, 759–761.

Allen, R. G. & Tresini, M. (2000). Oxidative stress and gene regulation. *Free Radic Biol Med* **28**, 463–499.

Anonymous (2014). ProMED-mail 2014. January 12, 2014, archive no. 20140118.2181682. Nipah encephalitis, human – Bangladesh (02). *Dhaka Tribune*

Anonymous (2015). ProMED-mail 2015. February 02, 2015, archive no. 20150204.3143251. Nipah encephalitis, human – Bangladesh. *Daily Star*

Casola, A., Burger, N., Liu, T., Jamaluddin, M., Brasier, A. R. & Garofalo, R. P. (2001). Oxidant tone regulates RANTES gene expression in airway epithelial cells infected with respiratory syncytial virus. Role in viral-induced interferon regulatory factor activation. *J Biol Chem* **276**, 19715–19722.

Castro, S. M., Guerrero-Plata, A., Suarez-Real, G., Adegboyega, P. A., Colasurdo, G. N., Khan, A. M., Garofalo, R. P. & Casola, A. (2006). Antioxidant treatment ameliorates respiratory syncytial virus-induced disease and lung inflammation. *Am J Respir Crit Care Med* **174**, 1361–1369.

Chong, H. T., Kunjapan, S. R., Thayaparan, T., Tong, J. M. G., Petharunam, V., Jusoh, M. R. & Tan, C. T. (2002). Nipah encephalitis outbreak in Malaysia, clinical features in patients from Seremban. *Can J Neurol Sci* **29**, 83–87.

Chua, K. B., Bellini, W. J., Rota, P. A., Harcourt, B. H., Tamin, A., Lam, S. K., Ksiazek, T. G., Rollin, P. E., Zaki, S. R. & other authors (2000).

Nipah virus: a recently emergent deadly paramyxovirus. *Science* **288**, 1432–1435.

Eaton, B. T., Broder, C. C. & Wang, L. F. (2005). Hendra and Nipah viruses: pathogenesis and therapeutics. *Curr Mol Med* **5**, 805–816.

Enserink, M. (2000). Emerging diseases. Malaysian researchers trace Nipah virus outbreak to bats. *Science* **289**, 518–519.

Escaffre, O., Borisevich, V., Carmical, J. R., Prusak, D., Prescott, J., Feldmann, H. & Rockx, B. (2013). Henipavirus pathogenesis in human respiratory epithelial cells. *J Virol* **87**, 3284–3294.

Gabbita, S. P., Robinson, K. A., Stewart, C. A., Floyd, R. A. & Hensley, K. (2000). Redox regulatory mechanisms of cellular signal transduction. *Arch Biochem Biophys* **376**, 1–13.

Garofalo, R., Sabry, M., Jamaluddin, M., Yu, R. K., Casola, A., Ogra, P. L. & Brasier, A. R. (1996). Transcriptional activation of the interleukin-8 gene by respiratory syncytial virus infection in alveolar epithelial cells: nuclear translocation of the RelA transcription factor as a mechanism producing airway mucosal inflammation. *J Virol* **70**, 8773–8781.

Garofalo, R. P., Kolli, D. & Casola, A. (2013). Respiratory syncytial virus infection: mechanisms of redox control and novel therapeutic opportunities. *Antioxid Redox Signal* **18**, 186–217.

Goh, K. J., Tan, C. T., Chew, N. K., Tan, P. S., Kamarulzaman, A., Sarji, S. A., Wong, K. T., Abdullah, B. J., Chua, K. B. & Lam, S. K. (2000). Clinical features of Nipah virus encephalitis among pig farmers in Malaysia. *N Engl J Med* **342**, 1229–1235.

Gurley, E. S., Montgomery, J. M., Hossain, M. J., Bell, M., Azad, A. K., Islam, M. R., Molla, M. A., Carroll, D. S., Ksiazek, T. G. & other authors (2007). Person-to-person transmission of Nipah virus in a Bangladeshi community. *Emerg Infect Dis* **13**, 1031–1037.

Harcourt, B. H., Lowe, L., Tamin, A., Liu, X., Bankamp, B., Bowden, N., Rollin, P. E., Comer, J. A., Ksiazek, T. G. & other authors (2005). Genetic characterization of Nipah virus, Bangladesh, 2004. *Emerg Infect Dis* **11**, 1594–1597.

Harit, A. K., Ichhpujani, R. L., Gupta, S., Gill, K. S., Lal, S., Ganguly, N. K. & Agarwal, S. P. (2006). Nipah/Hendra virus outbreak in Siliguri, West Bengal, India in 2001. *Indian J Med Res* **123**, 553–560.

Hosakote, Y. M., Liu, T., Castro, S. M., Garofalo, R. P. & Casola, A. (2009). Respiratory syncytial virus induces oxidative stress by modulating antioxidant enzymes. *Am J Respir Cell Mol Biol* **41**, 348–357.

Hosakote, Y. M., Jantzi, P. D., Esham, D. L., Spratt, H., Kurosky, A., Casola, A. & Garofalo, R. P. (2011). Viral-mediated inhibition of antioxidant enzymes contributes to the pathogenesis of severe respiratory syncytial virus bronchiolitis. *Am J Respir Crit Care Med* **183**, 1550–1560.

Hosakote, Y. M., Komaravelli, N., Mautemps, N., Liu, T., Garofalo, R. P. & Casola, A. (2012). Antioxidant mimetics modulate oxidative stress and cellular signaling in airway epithelial cells infected with respiratory syncytial virus. *Am J Physiol Lung Cell Mol Physiol* **303**, L991–L1000.

Hossain, M. J., Gurley, E. S., Montgomery, J. M., Bell, M., Carroll, D. S., Hsu, V. P., Formenty, P., Croisier, A., Bertherat, E. & other authors (2008). Clinical presentation of Nipah virus infection in Bangladesh. *Clin Infect Dis* **46**, 977–984.

Kashanian, S. & Ezzati Nazhad Dolatabadi, J. (2009). *In vitro* study of calf thymus DNA interaction with butylated hydroxyanisole. *DNA Cell Biol* **28**, 535–540.

Kim, C. H., Kim, J. H., Hsu, C. Y. & Ahn, Y. S. (1999). Zinc is required in pyrrolidine dithiocarbamate inhibition of NF-κB activation. *FEBS Lett* **449**, 28–32.

Kinnula, V. L. & Crapo, J. D. (2003). Superoxide dismutases in the lung and human lung diseases. *Am J Respir Crit Care Med* **167**, 1600–1619.

Knobil, K., Choi, A. M., Weigand, G. W. & Jacoby, D. B. (1998). Role of oxidants in influenza virus-induced gene expression. *Am J Physiol* **274**, L134–L142.

Kong, A. N., Owuor, E., Yu, R., Hebbar, V., Chen, C., Hu, R. & Mandlekar, S. (2001). Induction of xenobiotic enzymes by the MAP kinase pathway and the antioxidant or electrophile response element (ARE/EpRE). *Drug Metab Rev* **33**, 255–271.

Lo, M. K. & Rota, P. A. (2008). The emergence of Nipah virus, a highly pathogenic paramyxovirus. *J Clin Virol* **43**, 396–400.

MacNee, W. (2001). Oxidative stress and lung inflammation in airways disease. *Eur J Pharmacol* **429**, 195–207.

Marsh, G. A. & Wang, L. F. (2012). Hendra and Nipah viruses: why are they so deadly? *Curr Opin Virol* **2**, 242–247.

Morcillo, E. J., Estrela, J. & Cortijo, J. (1999). Oxidative stress and pulmonary inflammation: pharmacological intervention with antioxidants. *Pharmacol Res* **40**, 393–404.

Oxford, J. S. & Perrin, D. D. (1974). Inhibition of the particle-associated RNA-dependent RNA polymerase activity of influenza viruses by chelating agents. *J Gen Virol* **23**, 59–71.

Paton, N. I., Leo, Y. S., Zaki, S. R., Auchus, A. P., Lee, K. E., Ling, A. E., Chew, S. K., Ang, B., Rollin, P. E. & other authors (1999). Outbreak of Nipah-virus infection among abattoir workers in Singapore. *Lancet* **354**, 1253–1256.

Premalatha, G. D., Lye, M. S., Ariokasamy, J., Parashar, U. D., Rahmat, R., Lee, B. Y. & Ksiazek, T. G. (2000). Assessment of Nipah virus transmission among pork sellers in Seremban, Malaysia. *Southeast Asian J Trop Med Public Health* **31**, 307–309.

Pyo, C. W., Shin, N., Jung, K. I., Choi, J. H. & Choi, S. Y. (2014). Alteration of copper-zinc superoxide dismutase 1 expression by influenza A virus is correlated with virus replication. *Biochem Biophys Res Commun* **450**, 711–716.

Rahman, M. A., Hossain, M. J., Sultana, S., Homaira, N., Khan, S. U., Rahman, M., Gurley, E. S., Rollin, P. E., Lo, M. K. & other authors (2012). Date palm sap linked to Nipah virus outbreak in Bangladesh, 2008. *Vector Borne Zoonotic Dis* **12**, 65–72.

Reed, L. J. & Muench, H. (1938). A simple method of estimating fifty per cent endpoints. *Am J Hyg* **27**, 493–497.

Riva, D. A., Ríos de Molina, M. C., Rocchetta, I., Gerhardt, E., Coulombié, F. C. & Mersich, S. E. (2006). Oxidative stress in Vero cells infected with vesicular stomatitis virus. *Intervirology* **49**, 294–298.

Rockx, B., Brining, D., Kramer, J., Callison, J., Ebihara, H., Mansfield, K. & Feldmann, H. (2011). Clinical outcome of henipavirus infection in hamsters is determined by the route and dose of infection. *J Virol* **85**, 7658–7671.

Rockx, B., Winegar, R. & Freiberg, A. N. (2012). Recent progress in henipavirus research: molecular biology, genetic diversity, animal models. *Antiviral Res* **95**, 135–149.

Uchide, N. & Toyoda, H. (2011). Antioxidant therapy as a potential approach to severe influenza-associated complications. *Molecules* **16**, 2032–2052.

Uchide, N., Ohyama, K., Bessho, T., Yuan, B. & Yamakawa, T. (2002). Effect of antioxidants on apoptosis induced by influenza virus infection: inhibition of viral gene replication and transcription with pyrrolidine dithiocarbamate. *Antiviral Res* **56**, 207–217.

Valbuena, G., Halliday, H., Borisevich, V., Goez, Y. & Rockx, B. (2014). A human lung xenograft mouse model of Nipah virus infection. *PLoS Pathog* **10**, e1004063.

Wong, K. T., Shieh, W. J., Kumar, S., Norain, K., Abdullah, W., Guarner, J., Goldsmith, C. S., Chua, K. B., Lam, S. K. & other authors (2002). Nipah virus infection: pathology and pathogenesis of an emerging paramyxoviral zoonosis. *Am J Pathol* **161**, 2153–2167.

Yamada, Y., Limmon, G. V., Zheng, D., Li, N., Li, L., Yin, L., Chow, V. T., Chen, J. & Engelward, B. P. (2012). Major shifts in the spatio-temporal distribution of lung antioxidant enzymes during influenza pneumonia. *PLoS One* **7**, e31494.

Yuan, X., Xu, C., Pan, Z., Keum, Y. S., Kim, J. H., Shen, G., Yu, S., Oo, K. T., Ma, J. & Kong, A. N. (2006). Butylated hydroxyanisole regulates ARE-mediated gene expression via Nrf2 coupled with ERK and JNK signaling pathway in HepG2 cells. *Mol Carcinog* **45**, 841–850.