Characterization of neutrophil extracellular traps in cats naturally infected with feline leukemia virus

Amanda B. Wardini, 1 Anderson B. Guimarães-Costa, 2 Michelle T. C. Nascimento, 2 Natalia R. Nadaes, 1 Maria G. M. Danelli, 1 Carlos Mazur, 1 Claudia F. Benjamin, 3 Elvira M. Saraiva 2 and Lucia H. Pinto-da-Silva 1

1 Instituto de Veterinária, Universidade Federal Rural do Rio de Janeiro (UFRRJ), Seropédica, RJ, Brazil
2 Instituto de Microbiologia Prof. Paulo de Gôes, Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, RJ, Brazil
3 Departamento de Farmacologia Básica e Clínica, Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, RJ, Brazil

Feline leukemia virus (FeLV), a common, naturally occurring gammaretrovirus in domestic cats, is associated with degenerative diseases of the haematopoietic system, immunodeficiency and neoplasia. FeLV infection causes an important suppression of neutrophil function, leading to opportunistic infections. Recently, a new microbicidal mechanism named NETosis was described in human, bovine and fish neutrophils, as well as in chicken heterophils. The purpose of the present study was to characterize NETosis in feline neutrophils, as well as to evaluate neutrophil function in FeLV naturally infected symptomatic and asymptomatic cats through the phagocytosis process, release of neutrophil extracellular traps (NETs) and myeloperoxidase (MPO) activity. The results showed that feline neutrophils stimulated with protozoa parasites released structures comprising DNA and histones, which were characterized as NETs by immunofluorescence. Quantification of NETs after neutrophil stimulation showed a significant increase in NET release by neutrophils from FeLV - and FeLV + asymptomatic cats compared with FeLV + symptomatic cats. Moreover, the number of released NETs and MPO activity in unstimulated neutrophils of FeLV + symptomatic cats were higher than those in unstimulated neutrophils from FeLV - and FeLV + asymptomatic cats. This study reports, for the first time, NET release by feline neutrophils, along with the fact that NET induction may be modulated by a viral infection. The results indicate that the NET mechanism appears to be overactivated in FeLV + cats and that this feature could be considered a marker of disease progression in FeLV infection.

INTRODUCTION

Neutrophils are among the first cells involved in the defence against pathogens such as bacteria, fungi and protozoa. These cells utilize mechanisms such as phagocytosis, degranulation and oxidative burst to efficiently kill and eliminate micro-organisms (Nathan, 2006). Recently, a new microbicidal mechanism named NETosis was described in human, bovine and fish neutrophils, as well as in chicken heterophils (Brinkmann et al., 2004; Lippolis et al., 2006; Palić et al., 2007; Chuammitri et al., 2009). In this mechanism, neutrophils die after releasing ‘neutrophil extracellular traps’ (NETs), threads composed of DNA, histones and granular proteins that not only ensnare microorganisms but also provide a high local concentra-

tion of antimicrobial molecules (Brinkmann et al., 2004; Lippolis et al., 2006; Urban et al., 2006; Guimarães-Costa et al., 2009). The release of NETs is dependent on reactive oxygen species (ROS) production and can be stimulated by bacteria, fungi, protozoa and some soluble molecules (e.g. interleukin-8, lipopolysaccharide, β-glucan and phorbol esters) (Brinkmann et al., 2004; Lippolis et al., 2006; Urban et al., 2006; Fuchs et al., 2007; Chuammitri et al., 2009; Guimarães-Costa et al., 2009).

Feline leukemia virus (FeLV) is a naturally occurring gammaretrovirus found worldwide in domestic cats and some small, related felids (Hoover & Mullins, 1991; Leutenegger et al., 1999). FeLV is a horizontally transmitted virus that can lead to fatal neoplasia, degenerative diseases of the haematopoietic system and immunodeficiency (Dunham & Graham, 2008). There is interest in this
The aim of this study was to analyse NETs from healthy different stimuli (Kiehl et al., 1987; Dezzutti et al., 1989), as the loss of neutrophil function has also been reported as a consequence of FeLV infection. Moreover, neutrophils from FeLV-infected cats suffer reduced ROS production, phagocytosis and chemotaxis (Lafrado & Olsen, 1986; Lewis et al., 1986; Kiehl et al., 1987; Lafrado et al., 1987).

The aim of this study was to analyse NETs from healthy (FeLV−) and FeLV naturally infected (FeLV+) symptomatic and asymptomatic cats. We have demonstrated for the first time that cat neutrophils release pathogen-induced NETs and that, most significantly, NET induction is associated with the health status of FeLV-infected cats.

RESULTS AND DISCUSSION

Neutrophil phagocytosis

Neutrophils are among the first leukocytes to reach the site of infection and play important roles in immune responses to infection. Previous studies have demonstrated that FeLV infection affects neutrophil function and their response to different stimuli (Kiehl et al., 1987; Dezzutti et al., 1989, 1990; Hoffmann-Jagielska et al., 2005). Thus, neutrophils from FeLV+ experimentally infected and clinically ill cats show a reduced chemotactic response in vitro in comparison with neutrophils from FeLV− cats (Kiehl et al., 1987). Using flow cytometry, Hoffmann-Jagielska et al. (2005) demonstrated that neutrophils from naturally infected animals, although clinically asymptomatic, presented an impaired phagocytic capacity compared with neutrophils from FeLV− animals. In their study, although the mean number of bacteria phagocytosed was similar, differences in the percentage of cells able to phagocytose Escherichia coli were observed. In our work, the phagocytic capacity of purified neutrophils from FeLV−, FeLV+ asymptomatic and FeLV+ symptomatic cats was evaluated in vitro using Leishmania promastigotes. Our results showed that the neutrophils obtained from these different groups were able to bind and phagocytose promastigote forms of Leishmania regardless of their FeLV infection status. No difference was observed in the number of parasites phagocytosed per neutrophil (FeLV−: 1.107 ± 0.06; FeLV+ asymptomatic: 1.104 ± 0.07; FeLV+ symptomatic: 1.146 ± 0.05), in the percentage of infected neutrophils (FeLV−: 48 ± 13.5%; FeLV+ asymptomatic: 49.5 ± 11.3%; FeLV+ symptomatic: 47 ± 13%) or in the infectivity index (FeLV− = 26.07 ± 2.65; FeLV+ asymptomatic = 27.02 ± 2.69; FeLV+ symptomatic = 27.62 ± 2.86) among the studied groups, indicating that the recognition and uptake mechanisms involved in Leishmania ingestion by neutrophils are not affected by FeLV infection. These apparently contradictory results could be explained by methodological differences and by the specific micro-organisms used to evaluate neutrophil phagocytic properties, or by the particles utilized, given that Leishmania can be recognized by lipophosphoglycan and glycoprotein 63 (gp63) surface molecules (Van Strijp et al., 1993).

Characterization of feline NETs

The NETosis process has an important microbicidal function, as demonstrated in human neutrophils during infection with bacteria, fungi and Leishmania (Brinkmann et al., 2004; Urban et al., 2006; Guimarães-Costa et al., 2009), as well as in bovine neutrophils during mastitis infection (Lippolis et al., 2006). Generation of oxygen radicals has been associated with NET release (Fuchs et al., 2007). Thus, exogenous H2O2 generated from NADPH oxidase induced NET release in mammals and release of heterophil extracellular traps in chickens (Fuchs et al., 2007; Chumamitri et al., 2009). FeLV infection inhibits neutrophil activation by inhibition of protein kinase C and a decrease in ROS production (Lafrado & Olsen, 1986; Lewis et al., 1986; Lafrado et al., 1987; Dezzutti et al., 1989, 1990; Hoffmann-Jagielska et al., 2005).

We therefore initially characterized the capacity of healthy cat neutrophils to release NETs following incubation with Leishmania promastigotes. A classical NET fibrous structure protruding extracellularly from neutrophils entrapping a number of parasites was observed by optical microscopy, indicating the ability of cat neutrophils to release NETs following Leishmania stimulus (Fig. 1a, b). As histone is a known NET-associated component, we stained NETs with 4,6-diamidino-2-phenylindole (DAPI) and anti-H2A histone antibody (Fig. 1c, d). We found promastigotes ensnared by meshes labelled by these two markers (Fig. 1c, d). Secondary control antibody did not label the parasites (Fig. 1h) or the neutrophils (data not shown). To demonstrate the DNA content of these meshes further, DNase was added to the promastigote–cat neutrophil interaction. It was seen that digested NETs disappeared after enzymic treatment, confirming the presence of DNA in NETs released by feline neutrophils (Fig. 2).

NET release and myeloperoxidase (MPO) activity

Previous studies have shown that FeLV infection impairs neutrophil microbicidal functions and that affected cats are more susceptible to opportunistic infections (Lafrado & Olsen, 1986; Lewis et al., 1986). Decreased activation of
neutrophils from FeLV experimentally infected animals during phagocytosis of serum-opsonized particles has been described previously (Lewis et al., 1986). Likewise, neutrophils from FeLV+ animals were not activated by opsonized particles with serum obtained from FeLV+ cats (Lewis et al., 1986). Dezzutti et al. (1989, 1990) demonstrated that neutrophils from experimentally viraemic cats presented reduced protein kinase C activation when stimulated by phorbol myristate acetate (PMA). Similarly, neutrophils from healthy cats exposed to inactivated FeLV or purified p15E FeLV protein resulted in a diminished response to Ca2+ ionophore (Lafrado et al., 1987).

Moreover, a reduction in the oxidative activity of neutrophils from FeLV naturally infected asymptomatic animals was observed after stimulation with E. coli and/or PMA (Hoffmann-Jagielska et al., 2005).

Thus, we decided to quantify spontaneous (unstimulated) and Leishmania-stimulated NET release into supernatants from the neutrophils in the cat groups under analysis. NETs released by neutrophils obtained from FeLV− and FeLV+ asymptomatic cats increased around nine- and threefold after parasite stimulation in relation to unstimulated neutrophils, respectively (Fig. 3a, b). In contrast, neutrophils from FeLV+ symptomatic cats were not able to significantly increase NET release upon parasite stimulation (Fig. 3c). The same inability to induce NETs was observed in neutrophils from PMA-stimulated symptomatic cats (data not shown). Taken together, these

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**Fig. 1.** Characterization of feline NETs. (a–e) Cat neutrophils were stimulated with promastigotes (cell:parasite ratio of 1:5) at 34 °C and 5% CO2 for 2 h. Cells were fixed with paraformaldehyde and stained with Diff-Quick (a, b), DAPI (5 ng ml⁻¹) (c) or anti-histone H2A (diluted 1:800) (d). In (c), an overlay of differential interference contrast (DIC) and DAPI fluorescence shows a parasite (arrowhead) ensnared by the NET (arrow). (e) Merged image of DAPI staining (blue) and anti-histone (red) fluorescence showing pink staining resulting from the overlay of images. (f–h) DIC of paraformaldehyde-fixed Leishmania promastigotes (f), DAPI staining (5 ng ml⁻¹) of the promastigote nucleus and kinetoplast (g) and anti-histone labelling (h). N, Neutrophils. Bars, 20 μm (a–e); 4 μm (f–h).

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**Fig. 2.** DNase eliminates feline NET formation. Cat neutrophils were stimulated with promastigotes (cell:parasite ratio of 1:5) at 34 °C and 5% CO2 for 2 h. Cells were fixed with paraformaldehyde and stained in the absence (a, b) or presence (c, d) of DNase (50 IU ml⁻¹) for 2 h and then incubated with DAPI (5 ng ml⁻¹). (a, b) DIC (a) and fluorescent image (b) of Leishmania entrapped by NETs (arrowheads) stained by DAPI (arrow). (c, d) Phagocytosis of Leishmania (arrowhead) and a degraded NET (arrow) following enzymatic treatment with DNase shown by DIC (c) and fluorescence (d). N, Neutrophils. Bars, 20 μm.

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findings suggest that FeLV infection could lead to an exacerbated neutrophil activation, making these cells unresponsive to new stimuli. Interestingly, when NETs released from unstimulated neutrophils were compared, it was observed that neutrophils from FeLV + symptomatic animals produced 15 and 2.3 times more NETs than unstimulated neutrophils from FeLV − and FeLV + asymptomatic cats, respectively (Fig. 3d).

Several granular proteins, such as elastase, MPO, cathepsin G, lactoferrin and gelatinase, are released in association with NETs (Brinkmann et al., 2004). MPO is an important enzyme involved in oxidative stress and in the inflammatory process itself (Loria et al., 2008). Thus, to characterize further the NET release from neutrophils, MPO activity was quantified in the supernatants of unstimulated cells in the different cat groups being studied. The increase in MPO activity was similar to the increase in DNA concentration measured in the unstimulated neutrophils tested (Fig. 4). Furthermore, MPO activity increased in unstimulated neutrophils from FeLV + symptomatic animals compared with healthy ones, implying spontaneous neutrophil activation during progressive FeLV infection. Altered neutrophil functions have been detected in other viral infections, particularly with human immunodeficiency virus type 1 and human T-lymphotropic virus type 1 (Guerreiro et al., 2005; Salmen et al., 2007). An increase in NET release and MPO activity in unstimulated neutrophils from FeLV + symptomatic cats was also observed, suggesting that progressive viral infections may induce chronic neutrophil activation.

In this report, along with the finding that NET induction may be modulated by a viral infection, NET release by feline neutrophils is described for the first time. Overall, our results indicate that the NET mechanism appears to be exhausted in FeLV + animals, preventing a neutrophil response to other stimuli. We believe that this feature could be considered a marker of disease progression and an important neutrophil trait in FeLV infection, similar to what has been described recently for sepsis and septic arthritis (Margraf et al., 2008; Lógters et al., 2009).

**METHODS**

**Animals.** The experimental group consisted of male cats ranging from 1 to 7 years old, which were evaluated with regard to their haemogram, body mass and temperature, dehydration status, appetite, faeces, mucosal cavities, lymph nodes and the presence of tumour mass. None of the cats presented any laboratory or clinical

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Fig. 3. NET quantification of cat neutrophils. FeLV − (a), FeLV + asymptomatic (b) and FeLV + symptomatic (c) neutrophils were stimulated with *Leishmania* promastigotes for 2 h. Supernatants were recovered and NETs were quantified using a Picogreen dsDNA kit. In (d), basal NETs were measured using unstimulated or resting neutrophil supernatant. Data are expressed as means ± SEM. *P < 0.002, **P < 0.02, ***P < 0.001; n = 8 animals per group. N, Neutrophils; N + L, neutrophils plus *Leishmania*.

Fig. 4. MPO activity of unstimulated cat neutrophils. FeLV −, FeLV + asymptomatic and FeLV + symptomatic unstimulated neutrophils were used to evaluate the basal MPO activity of supernatants after 2 h incubation at 34 °C and 5% CO2. Data are expressed as means ± SEM, with n = 8 animals per group. *P > 0.05.
Neutrophils were recovered from the 1.119/1.007 interface, resus- 
evaled by a 0.01 % Trypan blue assay using a haemocytometer. 
resuspended in RPMI 1640 without serum and their viability was 

37 C were maintained for 1 h at 34 C and 5 % CO2. After 

cultures were washed twice in PBS (pH 7.2) with centrifugation at 1900 
gm l-1. Parasites were added to the adhered 

Neutrophils at a parasite : cell ratio of 5 : 1. After 2 h at 34 

neutrophils were incubated with promastigotes for 2 h, as described above, fixed 

and mounted in Permount (Fisher Scientific). The association index was obtained by 

by randomly counting at least 200 

parasites per infected neutrophil, by randomly counting at least 200 

were incubated with promastigotes (100.007/1.119, 

promastigotes were incubated with promastigotes for 2 h, as described above, fixed 

were washed twice in PBS (pH 7.2) with centrifugation at 1900 

37 C and 5 % CO2. After 

by Dr A. Zychlinsky, Max Planck Institute, Germany), followed by 

Promastigotes were added to the adhered 

Neutrophils (5 

Purified neutrophils (1 

Neutrophil–parasite interactions. Purified neutrophils (1 

Characterization of NETs. Purified neutrophils (1 

Quantification of NET released. Neutrophils (5 

MPO activity. Supernatants (50 ml) from unstimulated neutrophils 

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FeLV infection affects release of NETs

signs of concurrent infection, including haemotropic mycoplasmas 

(5 105 per well) 

were incubated with or without L. amazonensis at a promastigote : 

neutrophil ratio of 5:1. After 1 h, restriction enzymes (EcoR1 and 

HindIII, 20 U ml-1 each; New England BioLabs) were added to the 

cultures, which were maintained for 1 h at 34 C and 5 % CO2. After 

centrifugation, NETs were quantified in the culture supernatant using 

a PicoGreen dsDNA kit (Invitrogen) according to the manufacturer’s 

instructions. NET DNA concentrations were calculated using herring 

sperm DNA (Sigma) as a standard.

Different concentrations of lysed neutrophils were used as controls. 

Asbestos was determined at 405 nm using a microtitre plate 

spectrophotometer (V-Max; Molecular Devices) with SoftMax PRO 

4.0 software.

Statistical analysis. Data are presented as means±SEM and were 

analysed using Student’s t-test with Kruskall–Wallis or analysis of 

variance test corrections (GraphPad Prism 3.00).

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