

Elevated Serum Concentrations of Polymorphonuclear Neutrophilic Leukocyte Elastase in Systemic Sclerosis: Association with Pulmonary Fibrosis

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ABSTRACT. Objective. To determine the serum concentrations and clinical association of polymorphonuclear neutrophilic leukocyte (PMN) elastase in patients with systemic sclerosis (SSc).

Methods. Serum PMN elastase levels from 21 patients with limited cutaneous SSc (lSSc) and 32 with diffuse cutaneous SSc (dSSc) were examined by ELISA.

Results. Serum PMN elastase levels were elevated in patients with SSc, especially dSSc, compared to healthy controls. SSc patients with elevated serum PMN elastase levels had more frequent presence of pulmonary fibrosis, arthritis, contracture of phalanges, and diffuse pigmentation. Anticentromere antibody was detected less frequently in SSc patients with elevated serum PMN elastase levels than in controls. Consistently, serum PMN elastase levels also correlated positively with serum levels of KL-6 and surfactant protein-D, serological markers for pulmonary fibrosis. Serum PMN elastase levels were also associated with levels of serum 8-isoprostane, an oxidative stress marker in SSc.

Conclusion. Serum PMN elastase levels were elevated in patients with SSc, and it was more prominent in patients with pulmonary fibrosis, suggesting that serum PMN elastase is a novel serological marker for SSc-related pulmonary fibrosis. (First Release Oct 15 2008; J Rheumatol 2009; 36:99–105; doi:10.3899/jrheum.080269)

Key Indexing Terms:

POLYMORPHONUCLEAR NEUTROPHILIC LEUKOCYTE ELASTASE
SYSTEMIC SCLEROSIS PULMONARY FIBROSIS OXIDATIVE STRESS

Systemic sclerosis (SSc) is a multisystem disorder of connective tissue characterized by sclerotic changes in the skin and other visceral organs with an autoimmune background. The central event in SSc is an abnormal accumulation of extracellular matrix components¹⁻³. Although the pathogenesis of SSc remains unknown, interactions among lymphoid cells, endothelial cells, and fibroblasts are likely to be central to the pathogenesis of the disease. In early skin lesions of SSc, mononuclear cell infiltration, microvascular lesions, and increased extracellular matrix synthesis are first seen

around small vessels in the dermis⁴. Recent studies suggest that leukocyte migration is the first step of the multistep cascade involving cell adhesion molecules and chemokines⁵. Serine proteases, released from granulocytes and monocytes, are implicated directly or indirectly in the excessive deposition of extracellular matrix, being involved in marked conversion of latent matrix metalloproteinases (MMP) to lower molecular weight forms, active MMP that contribute to matrix remodeling⁶. Thus, collaborative interactions between serine proteases and MMP are generally presumed to contribute to the tissue destruction and extracellular matrix damage^{6,7}.

Polymorphonuclear neutrophilic leukocyte (PMN) elastase is one of the serine proteases found in the azurophilic granules of neutrophils⁸; it is capable by itself of degrading several different structural components such as collagen, fibronectin, proteoglycan, heparin, and cross-linked fibrin⁷. Studies have suggested that PMN and their products are involved in endothelial injury, inflammatory processes, and fibrosis⁷⁻¹¹. The activation of PMN leads to the release of multiple microbicidal products, including reactive oxygen species (ROS), cationic peptides, eicosanoids, and proteolytic enzymes⁸. PMN also release growth factors, cytokines, and chemokines, which can enhance the inflammatory response¹². Further, PMN elastase can enhance

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PMN migration by inducing the secretion of granulocyte-macrophage colony-stimulating factor, interleukin 6, and interleukin 8 from epithelial cells^{13,14}. A recent study suggests that an impairment in the ability of PMN to control hypoxia and inflammation could relate to the increased production of free oxygen radicals and consequent oxidative damage in SSc¹⁵. In addition, serine proteases and ROS have been suggested to be frequent companions at the sites of inflammation^{9,16}.

Passively released or actively secreted elastase from PMN has been linked to the pathologic processes of a variety of inflammatory diseases, including pulmonary fibrosis¹⁷⁻²⁰, rheumatoid arthritis²¹, sarcoidosis^{22,23}, adult respiratory distress syndrome^{24,25}, and cystic fibrosis^{14,26}. Pulmonary surfactant apoproteins are also digested by PMN elastase. Studies have reported that the number of PMN is elevated in bronchoalveolar lavage (BAL) fluid from SSc patients with active interstitial lung disease^{18,27}. Moreover, PMN elastase-deficient mice are resistant to bleomycin-induced fibrosis^{28,29}. Therefore, PMN and their products may be involved in either endothelial injury or inflammatory and fibrotic processes in SSc.

However, the prevalence or clinical significance of serum PMN elastase in SSc has not been clarified. We investigated whether PMN elastase was elevated in serum samples from patients with SSc, and whether serum PMN elastase levels correlated with the activity or severity of pulmonary fibrosis and other clinical symptoms in patients with SSc.

MATERIALS AND METHODS

Serum samples. Blood samples were obtained from 53 Japanese patients with SSc (44 women, 9 men; age 50 ± 16 yrs). All patients fulfilled the criteria proposed by the American College of Rheumatology³⁰. These patients were grouped according to the classification system proposed by LeRoy, *et al*³¹: 21 patients (19 women, 2 men; age 52 ± 13 yrs) had limited cutaneous SSc (lSSc) and 32 patients (25 women, 7 men; age 48 ± 18 yrs) had diffuse cutaneous SSc (dSSc). The disease duration of lSSc and dSSc patients was 7.4 ± 8.2 and 3.0 ± 2.9 years, respectively. The duration of disease was calculated from time of onset of the first clinical event (other than Raynaud's phenomenon) that was a clear manifestation of SSc. No patient had been treated with calcium antagonist, corticosteroid, D-penicillamine, or other immunosuppressive therapy at the evaluation. Antinuclear antibody was determined by indirect immunofluorescence using HEP-2 cells as the substrate, and autoantibody specificities were further assessed by enzyme-linked immunosorbent assay (ELISA) and immunoprecipitation. Anticentromere antibody (ACA) was positive for 17 patients (2 dSSc and 15 lSSc), anti-topoisomerase I antibody for 26 (22 dSSc and 4 lSSc), anti-U1RNP antibody for 2 (all dSSc), anti-U3RNP antibody for 1 (dSSc), anti-RNA polymerases I and III antibody for 6 (all dSSc), and anti-Th/To antibody for 1 (lSSc). Twenty-five age and sex-matched healthy Japanese individuals served as controls. Fresh venous blood samples were centrifuged shortly after clot formation. All samples were stored at -70°C prior to use.

The protocol was approved by the Kanazawa University Graduate School of Medical Science, and informed consent was obtained from all patients.

Clinical assessment. Complete medical histories, physical examinations, and laboratory tests were conducted for all patients at their first visit. Skin score was measured by the modified Rodnan total skin thickness score

(modified Rodnan TSS)³². The 17 anatomic areas were rated as 0 (normal skin thickness), 1+ (mild but definite skin thickening) 2+ (moderate skin thickening), and 3+ (severe skin thickening); and the modified Rodnan TSS was derived by summing the scores from all 17 areas (range 0-51). Organ system involvement was defined as described³³: lung = bibasilar fibrosis on chest radiography and high resolution computed tomography; esophagus = hypomotility shown by barium radiography; joint = inflammatory polyarthralgias or arthritis; heart = pericarditis, congestive heart failure, or arrhythmias requiring treatment; kidney = malignant hypertension and rapidly progressive renal failure without any other explanation; and muscle = proximal muscle weakness and elevated serum creatine kinase. Pulmonary function tests, including vital capacity (VC) and diffusion capacity for carbon monoxide (DLCO), were also done. When the DLCO and VC were $< 75\%$ and $< 80\%$, respectively, of predicted normal values, they were considered to be abnormal.

ELISA. Specific ELISA kits were used for measuring serum PMN elastase levels (Bender MedSystems, Vienna, Austria), according to the manufacturer's protocol. Each sample was tested in duplicate. Serum levels of ACA or anti-topoisomerase I antibody were assessed using specific ELISA kits (Medical & Biological Laboratories, Nagoya, Japan), according to the manufacturer's protocol. To assess oxidative stress, serum levels of 8-isoprostane, a reliable biomarker of oxidative stress^{34,35}, were also examined using a specific ELISA kit (Cayman Chemical Co., Ann Arbor, MI, USA), according to the manufacturer's protocol. Serum levels of KL-6 and surfactant protein-D (SP-D), both serological markers of pulmonary fibrosis, were investigated using specific ELISA kits (Eitest KL-6, Eisai, Tokyo, Japan, and SP-D kit, Yamasa, Chiba, Japan, respectively), according to the manufacturer's protocol.

Statistical analysis. Statistical analysis was performed by Mann-Whitney U test for comparison of serum PMN elastase levels, Fisher's exact probability test for comparison of frequencies, and Bonferroni's test for multiple comparisons. Spearman's rank correlation coefficient was used to examine the relationship between 2 continuous variables. A p value < 0.05 was considered statistically significant.

RESULTS

Serum PMN elastase levels in SSc. The levels and presence of PMN elastase in serum samples from SSc patients and healthy controls were assessed by ELISA (Figure 1a). Serum PMN elastase levels in dSSc patients were significantly higher than those in controls ($p < 0.0001$). Similarly, lSSc patients exhibited significantly elevated PMN elastase levels compared with controls ($p < 0.0005$). Optical density values higher than the mean + 2 SD (0.9 ng/ml) of control serum samples were considered to be elevated. Elevated serum PMN elastase levels were observed in 58% (31/53) of all SSc patients. Regarding the disease subsets, serum PMN elastase levels were increased in 69% (22/32) of dSSc patients, while 43% (9/21) of lSSc patients had elevated PMN elastase. In contrast, only 4% (1/25) of controls showed elevated PMN elastase levels. Thus, PMN elastase levels were elevated in SSc patients, especially in dSSc patients.

Clinical correlation of PMN elastase levels in SSc. Next we assessed clinical correlations of serum PMN elastase levels in SSc patients. Patients with elevated PMN elastase levels had more frequent presence of pulmonary fibrosis ($p < 0.05$), arthritis ($p < 0.05$), contracture of phalanges ($p < 0.01$), and diffuse pigmentation ($p < 0.005$) than those with

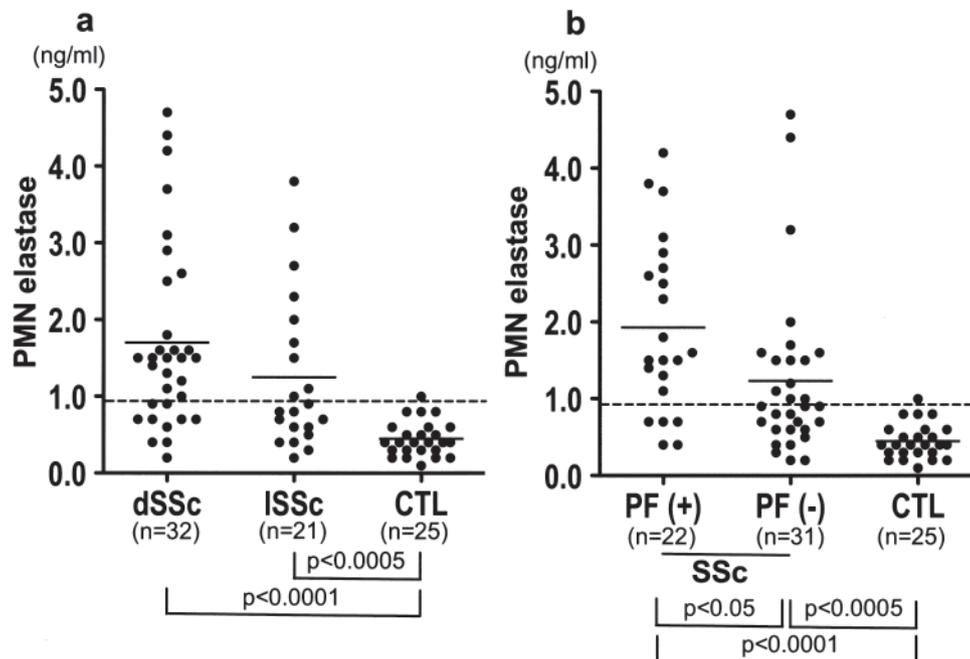


Figure 1. a. Serum PMN elastase levels in dSSc patients, ISSc patients, and healthy controls (CTL). b. Serum PMN elastase levels in SSc patients with pulmonary fibrosis [PF(+)], without pulmonary fibrosis [PF(-)], and controls. Serum PMN elastase levels were determined by a specific ELISA. Short bar indicates the mean value in each group. Broken line indicates the cutoff value (mean + 2 SD of control samples).

normal PMN elastase levels (Table 1). ACA was detected less frequently in SSc patients with elevated PMN elastase levels (18%) than those with normal levels (58%; $p < 0.005$). Conversely, the prevalence of anti-topoisomerase I antibody positivity tended to be higher in patients with elevated PMN elastase levels than those with normal levels (56% vs 37%; $p = 0.07$). Consistent with these findings, elevated PMN elastase levels were detected more frequently in dSSc patients (71%) than ISSc patients (29%; $p < 0.05$). To determine the correlations of serum PMN elastase levels with disease duration, we classified SSc patients into 2 groups: the early disease population (within 2 yrs from onset) and late disease population (more than 2 yrs from onset). Serum PMN elastase concentrations in the early disease population were significantly elevated compared with the late disease population (1.8 ± 1.0 vs 1.3 ± 1.4 ng/ml, respectively; $p < 0.05$). Although serum PMN elastase levels in dSSc patients tended to be higher than those in ISSc patients, in both early and late disease populations (data not shown), these differences were not statistically significant. Moreover, SSc patients with pulmonary fibrosis exhibited significantly elevated serum PMN elastase levels compared to SSc patients without pulmonary fibrosis ($p < 0.05$) and controls ($p < 0.0001$; Figure 1b). Similarly, serum PMN elastase levels in SSc patients without pulmonary fibrosis were significantly higher than those in controls ($p < 0.0005$). In addition, serum PMN elastase levels tended to correlate inversely with %DLCO ($r = -0.28$, $p = 0.07$) in SSc patients with pul-

Table 1. Clinical and laboratory data of patients with SSc showing elevated serum PMN elastase levels. Values of clinical features and organ involvement are percentages.

	Elevated Serum PMN Elastase, n = 34	Normal Serum PMN Elastase, n = 19
Age at onset, yrs, mean \pm SD	48 \pm 17	47 \pm 16
Sex, male:female	7:28	2:17
Disease duration, yrs, mean \pm SD	4.0 \pm 5.6	5.5 \pm 6.4
Clinical features		
dSSc	71*	42
ISSc	29	58*
Pitting scars	47	37
Contracture of phalanges	59**	21
Diffuse pigmentation	68***	26
Organ involvement		
Lung	54*	26
Decreased % VC	24	40
Decreased % DLco	64	86
Pulmonary hypertension	17	7
Esophagus	53	50
Heart	21	11
Kidney	12	33
Joint	32*	16
Muscle	26	21
Autoantibodies		
Antitopoisomerase I	56	37
Anticentromere	18	58***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.005$ vs SSc patients with normal PMN elastase levels.

monary fibrosis. Remarkably, serum PMN elastase in SSc patients showing markedly reduced VC (< 60%) was associated with decreased %VC ($r = -0.643$, $p < 0.05$) and the presence of pulmonary fibrosis ($p < 0.01$). Further, we investigated correlations of serum PMN elastase levels with serum levels of KL-6, which is a mucin-like high molecular-weight glycoprotein³⁶ and a marker of pulmonary fibrosis³⁷, and SP-D, which is produced and secreted by alveolar type II pneumocytes in alveoli and Clara cells and is a marker of pulmonary fibrosis³⁸. Serum PMN elastase levels correlated positively with serum KL-6 levels ($p < 0.05$, $r = 0.517$) and SP-D levels ($p < 0.05$, $r = 0.447$) determined by ELISA (Figure 2). Serum levels of 8-isoprostane, a reliable biomarker of oxidative stress, also correlated positively with serum PMN elastase levels ($p < 0.05$, $r = 0.329$). Thus, elevated PMN elastase in SSc patients was generally associated with disease severity, especially with the extent of pulmonary fibrosis.

DISCUSSION

Our study is the first to show that serum PMN elastase levels were elevated in patients with SSc, especially in patients with dSSc. Interestingly, serum PMN elastase levels in SSc correlated with the presence of pulmonary fibrosis. Consistent with these findings, serum PMN elastase levels correlated positively with the serum levels of KL-6 and SP-D, markers for monitoring the activity of pulmonary fibrosis^{38,39}. In addition, serum levels of PMN elastase in SSc

patients were associated with more frequent presence of arthritis, contracture of phalanges, and diffuse pigmentation. Further, serum PMN elastase levels correlated positively with serum levels of 8-isoprostane, a reliable biomarker of oxidative stress. These results indicate that serum PMN elastase is a novel serological marker for disease severity, especially for SSc-related pulmonary fibrosis.

Pulmonary complications are the leading cause of mortality in SSc^{40,41}. Early diagnosis and immunosuppressive treatment of pulmonary fibrosis may improve the prognosis of SSc patients⁴². Many studies have suggested that serum PMN elastase levels may be an indicator of disease activity of pulmonary interstitial disease^{19,25}. Consistently in our study, increased levels of serum PMN elastase were observed in SSc patients with pulmonary fibrosis. In addition, PMN elastase levels in BAL fluid are reported to be elevated in patients with pulmonary fibrosis¹⁸⁻²⁰, sarcoidosis^{22,23}, adult respiratory distress syndrome^{24,25}, cystic fibrosis^{14,26}, and SSc-related pulmonary fibrosis²⁷, and correlate with serum levels of PMN elastase^{20,43}. Although elevated levels of serum PMN elastase overall were associated with presence and severity of pulmonary fibrosis in SSc, the correlations between PMN elastase and the results of pulmonary function tests were not statistically significant. The recognition of interstitial lung manifestation in SSc may be delayed, because the clinical signs are often mild and onset is insidious^{44,45}. In some patients, lung function may remain stable for years, even in the later disease stage, while others

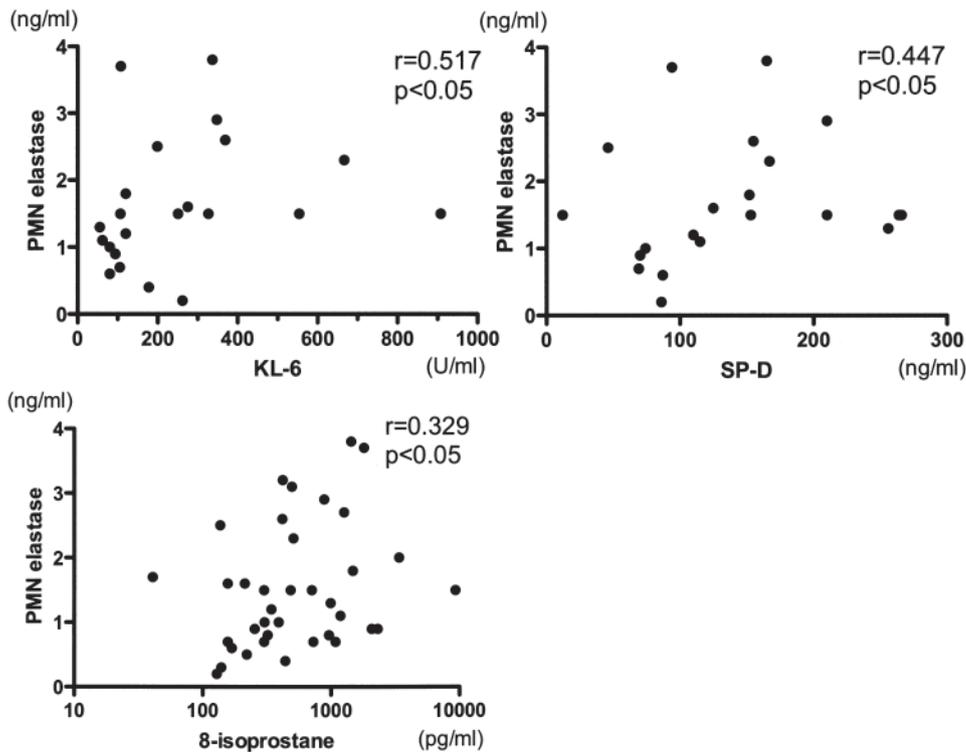


Figure 2. Correlation of PMN elastase levels against serum KL-6 levels, SP-D levels, and 8-isoprostane levels in patients with SSc. Serum PMN elastase, KL-6, SP-D, and 8-isoprostane concentrations were determined by ELISA.

may experience fatal progressive pulmonary fibrosis associated with SSc^{46,47}. These may be the reasons for the discrepancy between the extent of pulmonary fibrosis and the pulmonary function tests in SSc patients. At the same time, serum PMN elastase levels correlated positively with serum levels of KL-6 and SP-D, which are reported to be markers of pulmonary fibrosis, and the concentrations were associated with the activity of pulmonary fibrosis³⁸. Further, serum PMN elastase levels correlated positively with serum 8-isoprostane levels. A study has reported that serum 8-isoprostane levels correlate with the severity of pulmonary fibrosis, suggesting that serum 8-isoprostane is a useful serological marker for severity of lung fibrosis³⁵. Collectively, these results suggest that elevated PMN elastase is a novel serological marker for the severity of pulmonary fibrosis in patients with SSc.

SP-D plays important roles in innate immunity, and its expression increased rapidly following many types of lung injury^{48,49}. Additionally, SP-D levels were strongly correlated with KL-6 levels in sera from SSc patients³⁸. Recent studies reported that PMN elastase cleaved SP-D at sites of inflammation, with potential deleterious effects on its biological functions^{50,51}. SP-D-deficient mice show an exaggerated neutrophil response to viral and bacterial challenge⁵². Thus, SP-D could interact directly with PMN that infiltrate the lung in response to acute inflammation and infection. Moreover, PMN elastase increases oxidative stress in lung cells⁹. Antiproteases including α 1-proteinase inhibitor are sensitive to inactivation by oxidants released from activated neutrophils⁵³. Therefore, the toxic effect of PMN elastase is greatly enhanced by increased oxidative stress⁵⁴. Recently, increased adenosine deaminase activity and reduced adenosine receptor activity have been described in PMN from SSc patients, suggesting that impairment in the ability of PMN to control hypoxia and inflammation could relate to the increased production of free oxygen radicals and consequent oxidative damage in SSc¹⁵. Indeed, ischemia and reperfusion injury following Raynaud's phenomenon can generate ROS that may result in vascular endothelial damage^{55,56}. ROS could explain the tissue lesions in SSc, as free radicals can induce endothelial cell injury through peroxidation of lipid components of cell membrane, and may stimulate fibroblasts to proliferate and to produce increased amounts of collagen⁵⁷. Consistently in our study, serum PMN elastase levels were positively correlated with levels of serum 8-isoprostane, a marker of oxidative stress generated through cell-membrane oxidation^{34,35}. Thus, PMN elastase may participate in development of SSc by enhancing oxidative stress.

In addition, PMN elastase was also associated with more frequent presence of arthritis and contracture of phalanges. Previous studies showed that PMN elastase was elevated in destructive joints in RA²¹. In inflammatory lesions, MMP play a key role in matrix destruction^{58,59}. Serine proteases

such as PMN elastase, trypsin, plasminogen, plasminogen activator, and cathepsin G help activate these MMP^{60,61}. Studies have also suggested that these serine proteinases themselves, such as proteoglycanase, may cause cartilage matrix destruction⁶². Although the relationship between serine proteinases and MMP and the contribution of each factor to matrix destruction remain unclear, PMN elastase may play a role in damage to articular cartilage.

One study reported low elastase activity in circulating granulocytes of SSc patients⁶³. Although the reasons for this discrepancy remain unclear, it may be due to the differences in the patient population and treatment: the study⁶³ included SSc patients treated with a calcium antagonist (80%) that has antioxidant effects and antielastase activity^{64,65}, while such patients were excluded in our study. Nevertheless, these results suggest that elevated PMN elastase levels reflect the disease severity, especially pulmonary fibrosis, in patients with SSc. Future prospective and longitudinal studies are required to determine whether the changes in serum PMN elastase concentrations are correlated with new onset or deterioration of pulmonary fibrosis. The pathogenesis of SSc remains unknown — PMN elastase may play an important role in the initiation and development of this disease.

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REFERENCES

1. Jimenez SA, Htraya E, Varga J. Pathogenesis of scleroderma. *Collagen. Rheum Dis Clin North Am* 1996;22:647-74.
2. Lovell CR, Nicholls AC, Duance VC, Bailey AJ. Characterization of dermal collagen in systemic sclerosis. *Br J Dermatol* 1979;100:359-69.
3. LeRoy EC. Increased collagen synthesis by scleroderma skin fibroblasts in vitro: a possible defect in the regulation or activation of the scleroderma fibroblast. *J Clin Invest* 1974;54:880-9.
4. Sato S. Abnormalities of adhesion molecules and chemokines in scleroderma. *Curr Opin Rheumatol* 1999;11:503-7.
5. Ebnet K, Kaldjian EP, Anderson AO, Shaw S. Orchestrated information transfer underlying leukocyte endothelial interactions. *Annu Rev Immunol* 1997;14:155-77.
6. Zhu Y, Liu X, Sköld CM, et al. Collaborative interactions between neutrophil elastase and metalloproteinases in extracellular matrix degradation in three-dimensional collagen gels. *Respir Res* 2001;2:300-5.
7. Chua F, Laurent GJ. Neutrophil elastase: mediator of extracellular matrix destruction and accumulation. *Proc Am Thorac Soc* 2006;3:424-7.
8. Lee WL, Downey GP. Leukocyte elastase: physiological functions and role in acute lung injury. *Am J Respir Crit Care Med* 2001;164:896-904.
9. Aoshiba K, Yasuda K, Yasui S, Tamaoki J, Nagai A. Serine proteases increase oxidative stress in lung cells. *Am J Physiol Lung Cell Mol Physiol* 2001;281:L556-64.
10. Doring G. The role of neutrophil elastase in chronic inflammation. *Am J Respir Crit Care Med* 1994;150:S114-7.
11. Janoff A. Elastase in tissue injury. *Annu Rev Med* 1985;36:207-16.
12. Downey GP, Dong Q, Kruger J, Dedhar S, Cherapanov V. Regulation of neutrophil activation in acute lung injury. *Chest* 1999;116:46S-54S.

13. Nakamura H, Yoshimura K, McElvaney NG, Crystal RG. Neutrophil elastase in respiratory epithelial lining fluid of individuals with cystic fibrosis induces interleukin-8 gene expression in a human bronchial epithelial cell line. *J Clin Invest* 1992;89:1478-84.
14. Bedard M, McClure CD, Schiller NL, Francoeur C, Cantin A, Denis M. Release of interleukin-8, interleukin-6, and colony-stimulating factors by upper airway epithelial cells: implications for cystic fibrosis. *Am J Respir Cell Mol Biol* 1993;9:455-62.
15. Bazzichi L, Trincavelli L, Rossi A, et al. A2B adenosine receptor activity is reduced in neutrophils from patients with systemic sclerosis. *Arthritis Res Ther* 2005;7:R189-95.
16. Shao MX, Nadel JA. Neutrophil elastase induces MUC5AC mucin production in human airway epithelial cells via a cascade involving protein kinase C, reactive oxygen species, and TNF-alpha-converting enzyme. *J Immunol* 2005;175:4009-16.
17. Foerster J, Storch A, Fleischanderl S, et al. Neutrophil respiratory burst is decreased in scleroderma and normalized by near-infrared mediated hyperthermia. *Clin Exp Dermatol* 2006;31:799-806.
18. Cailles JB, O'Connor C, Pantelidis P, et al. Neutrophil activation in fibrosing alveolitis: a comparison of lone cryptogenic fibrosing alveolitis and systemic sclerosis. *Eur Respir J* 1996;9:992-9.
19. Borzi RM, Grigolo B, Meliconi R, et al. Elevated serum superoxide dismutase levels correlate with disease severity and neutrophil degranulation in idiopathic pulmonary fibrosis. *Clin Sci* 1993;85:353-9.
20. Obayashi Y, Yamadori I, Fujita J, Yoshinouchi T, Ueda N, Takahara J. The role of neutrophils in the pathogenesis of idiopathic pulmonary fibrosis. *Chest* 1997;112:1338-43.
21. Momohara S, Kashiwazaki S, Inoue K, Saito S, Nakagawa T. Elastase from polymorphonuclear leukocyte in articular cartilage and synovial fluids of patients with rheumatoid arthritis. *Clin Rheumatol* 1997;16:133-40.
22. Mordelet-Dambrine M, Lafuma C, Stanislas-Leguern G, Robert L, Chretien J, Hornebeck W. Elastase activity of bronchoalveolar cells in advanced pulmonary sarcoidosis. *Eur Resp J* 1988;1:748-57.
23. Peros-Golubic T, Ivcevic A, Bekic A, Alilovic M, Tekavec-Trkanjec J, Smojver-Jezek S. Lung lavage neutrophils, neutrophil elastase and albumin in the prognosis of pulmonary sarcoidosis. *Coll Antropol* 2001;25:349-55.
24. Fujishima S, Morisaki H, Ishizaka A, et al. Neutrophil elastase and systemic inflammatory response syndrome in the initiation and development of acute lung injury among critically ill patients. *Biomed Pharmacother* 2008;62:333-8.
25. Idell S, Kucich U, Fein A, et al. Neutrophil elastase-releasing factors in bronchoalveolar lavage from patients with adult respiratory distress syndrome. *Am Rev Respir Dis* 1985;132:1098-105.
26. Meyer KC, Lewandoski JR, Zimmerman JJ, Nunley D, Calhoun WJ, Dopico GA. Human neutrophil elastase and elastase/alpha 1-antiprotease complex in cystic fibrosis. Comparison with interstitial lung disease and evaluation of the effect of intravenously administered antibiotic therapy. *Am Rev Respir Dis* 1991;144:580-5.
27. Crestani B, Seta N, Palazzo E, et al. Interleukin-8 and neutrophils in systemic sclerosis with lung involvement. *Am J Respir Crit Care Med* 1994;150:1363-7.
28. Chua F, Dunsmore SE, Clingen PH, et al. Mice lacking neutrophil elastase are resistant to bleomycin-induced pulmonary fibrosis. *Am J Pathol* 2007;170:65-74.
29. Dunsmore SE, Roes J, Chua FJ, Segal AW, Mutsaers SE, Laurent GJ. Evidence that neutrophil elastase-deficient mice are resistant to bleomycin-induced fibrosis. *Chest* 2001;120:35S-36S.
30. Preliminary criteria for the classification of systemic sclerosis (scleroderma). Subcommittee for Scleroderma Criteria of the American Rheumatism Association Diagnostic and Therapeutic Criteria Committee. *Arthritis Rheum* 1980;23:581-90.
31. LeRoy EC, Black C, Fleischmajer R, et al. Scleroderma (systemic sclerosis): classification, subsets and pathogenesis. *J Rheumatol* 1988;15:202-5.
32. Clements PJ, Lachenbruch PA, Seibold JR, et al. Skin thickness score in systemic sclerosis: an assessment of interobserver variability in 3 independent studies. *J Rheumatol* 1993;20:1892-6.
33. Steen VD, Powell DL, Medsger TA Jr. Clinical correlations and prognosis based on serum autoantibodies in patients with systemic sclerosis. *Arthritis Rheum* 1988;31:196-203.
34. Morrow JD, Roberts LJ 2nd. The isoprostanes. Current knowledge and directions for future research. *Biochem Pharmacol* 1996;51:1-9.
35. Ogawa F, Shimizu K, Muroi E, et al. Serum levels of 8-isoprostane, a marker of oxidative stress, are elevated in patients with systemic sclerosis. *Rheumatology Oxford* 2006;45:815-8.
36. Kohno N, Akiyama M, Kyoizumi S, Hakoda M, Kobuke K, Yamakido M. Detection of soluble tumor-associated antigens in sera and effusions using novel monoclonal antibodies, KL-3 and KL-6, against lung adenocarcinoma. *Jpn J Clin Oncol* 1988;18:203-16.
37. Sato S, Nagaoka T, Hasegawa M, Nishijima C, Takehara K. Elevated serum KL-6 levels in patients with systemic sclerosis: association with the severity of pulmonary fibrosis. *Dermatology* 2000;200:196-201.
38. Yanaba K, Hasegawa M, Takehara K, Sato S. Comparative study of serum surfactant protein-D and KL-6 concentrations in patients with systemic sclerosis as markers for monitoring the activity of pulmonary fibrosis. *J Rheumatol* 2004;31:1112-20.
39. Yanaba K, Hasegawa M, Hamaguchi Y, Fujimoto M, Takehara K, Sato S. Longitudinal analysis of serum KL-6 levels in patients with systemic sclerosis: association with the activity of pulmonary fibrosis. *Clin Exp Rheumatol* 2003;21:429-36.
40. Silver RM. Scleroderma. Clinical problems. The lungs. *Rheum Dis Clin North Am* 1996;22:825-40.
41. Steen VD, Conte C, Owens GR, Medsger TA Jr. Severe restrictive lung disease in systemic sclerosis. *Arthritis Rheum* 1994;37:1283-9.
42. Silver RM, Miller KS, Kinsella MB, Smith EA, Schabel SI. Evaluation and management of scleroderma lung disease using bronchoalveolar lavage. *Am J Med* 1990;88:470-6.
43. Yamanouchi H, Fujita J, Hojo S, et al. Neutrophil elastase: alpha-1-proteinase inhibitor complex in serum and bronchoalveolar lavage fluid in patients with pulmonary fibrosis. *Eur Respir J* 1998;11:120-5.
44. Witt C, Borges AC, John M, Fietze I, Baumann G, Krause A. Pulmonary involvement in diffuse cutaneous systemic sclerosis: bronchoalveolar fluid granulocytosis predicts progression of fibrosing alveolitis. *Ann Rheum Dis* 1999;58:635-40.
45. De Santis M, Bosello S, La Torre G, et al. Functional, radiological and biological markers of alveolitis and infections of the lower respiratory tract in patients with systemic sclerosis. *Respir Res* 2005;6:96.
46. Wallaert B, Hatron PY, Grosbois JM, Tonnel AB, Devulder B, Voisin C. Subclinical pulmonary involvement in collagen-vascular diseases assessed by bronchoalveolar lavage. Relationship between alveolitis and subsequent changes in lung function. *Am Rev Respir Dis* 1986;133:574-80.
47. Rudd RM, Haslam PL, Turner-Warwick M. Cryptogenic fibrosing alveolitis. Relationships of pulmonary physiology and bronchoalveolar lavage to response to treatment and prognosis. *Am Rev Respir Dis* 1981;124:1-8.
48. Crouch E, Wright JR. Surfactant proteins a and d and pulmonary host defense. *Annu Rev Physiol* 2001;63:521-54.

49. McIntosh JC, Swyers AH, Fisher JH, Wright JR. Surfactant proteins A and D increase in response to intratracheal lipopolysaccharide. *Am J Respir Cell Mol Biol* 1996;15:509-19.
50. Cooley J, McDonald B, Accurso FJ, Crouch EC, Remold-O'Donnell E. Patterns of neutrophil serine protease-dependent cleavage of surfactant protein D in inflammatory lung disease. *J Leukoc Biol* 2008;83:946-55.
51. Hirche TO, Crouch EC, Espinola M, et al. Neutrophil serine proteinases inactivate surfactant protein D by cleaving within a conserved subregion of the carbohydrate recognition domain. *J Biol Chem* 2004;279:27688-98.
52. LeVine AM, Whitsett JA, Hartshorn KL, Crouch EC, Korfhagen TR. Surfactant protein D enhances clearance of influenza A virus from the lung in vivo. *J Immunol* 2001;167:5868-73.
53. Boudier C, Bieth JG. Oxidized mucus proteinase inhibitor: a fairly potent neutrophil elastase inhibitor. *Biochem J* 1994;303:61-8.
54. Zeiher BG, Matsuoka S, Kawabata K, Repine JE. Neutrophil elastase and acute lung injury: prospects for sivelestat and other neutrophil elastase inhibitors as therapeutics. *Crit Care Med* 2002;30:S281-7.
55. Butler AR, Flitney FW, Williams DL. NO, nitrosonium ions, nitroxide ions, nitrosothiols and iron-nitrosyls in biology: a chemist's perspective. *Trends Pharmacol Sci* 1995;16:18-22.
56. Suematsu M, Wakabayashi Y, Ishimura Y. Gaseous monoxides: a new class of microvascular regulator in the liver. *Cardiovasc Res* 1996;32:679-86.
57. Murrell DF. A radical proposal for the pathogenesis of scleroderma. *J Am Acad Dermatol* 1993;28:78-85.
58. Martel-Pelletier J, Pelletier JP. Neutral proteases in human osteoarthritic synovium: quantification and characterization. *J Rheumatol* 1987;14:38-40.
59. Okada Y, Nagase H, Harris ED Jr. Matrix metalloproteinases 1, 2, and 3 from rheumatoid synovial cells are sufficient to destroy joints. *J Rheumatol* 1987;14:41-2.
60. Nagase H, Enghild JJ, Suzuki K, Salvesen G. Stepwise activation mechanisms of the precursor of matrix metalloproteinase 3 (stromelysin) by proteinases and (4-aminophenyl) mercuric acetate. *Biochemistry* 1990;29:5783-9.
61. Campbell IK, Piccoli DS, Butler DM, Singleton DK, Hamilton JA. Recombinant human interleukin-1 stimulates human articular cartilage to undergo resorption and human chondrocytes to produce both tissue- and urokinase-type plasminogen activator. *Biochim Biophys Acta* 1988;967:183-94.
62. McDonnell J, Lobner JM, Knight WB, et al. Comparison of the proteoglycanolytic activities of human leukocyte elastase and human cathepsin G in vitro and in vivo. *Connect Tissue Res* 1993;30:1-9.
63. Bazzichi L, Rossi A, Giannaccini G, et al. Decreased elastase activity in circulating granulocytes of systemic sclerosis patients: a possible pathogenetic role. *Scand J Rheumatol* 2005;34:494-5.
64. Kouoh F, Gressier B, Dine T, et al. Antioxidant effects and anti-elastase activity of the calcium antagonist nifedipine on activated human and rabbit neutrophils — a potential antiatherosclerotic property of calcium antagonists? *Cardiovasc Drugs Ther* 2002;16:515-20.
65. Khalfi F, Gressier B, Brunet C, et al. Effects of calcium antagonist diltiazem on leukocyte elastase and on reactive oxygen species production in human neutrophils. *Pharmacol Res* 1996;33:117-22.