Cigarette smoke extract induces oxidative stress and apoptosis in human lung fibroblasts

Stefano Carnevali,1 Stefano Petruzzelli,1 Biancamaria Longoni,2 Renato Vanacore,3 Roberto Barale,4 Monica Cipollini,4 Fabrizio Scatena,3 Pierluigi Paggiaro,1 Alessandro Celi, and Carlo Giuntini1
1Pulmonary Unit, Cardiothoracic Department, Pharmacology Unit, Departments of 2Neuroscience and 3Human and Environmental Sciences, University of Pisa; and 4Blood Transfusion Section, Cisanello Hospital, 56124 Pisa, Italy

Submitted 6 December 2001; accepted in final form 21 January 2003

Cigarette smoke is the major cause of pulmonary emphysema. Epidemiological and clinical studies have shown that smokers are significantly more likely to develop emphysema compared with nonsmokers, and the seriousness of the disease is directly correlated with the amount of cigarette smoking (2, 20, 34). Among the different toxic effects of cigarette smoke on human tissues, oxidation of structural and functional molecules and modulation of cell turnover play a major role (29). For instance, Kasahara and coworkers (18) hypothesized that cigarette smoke may act by decreasing the expression of vascular endothelial growth factor (VEGF) and its type 2 receptor, thus resulting in lung septal endothelial cell death. Because fibroblasts play a pivotal role in remodeling of pulmonary tissue, we have exposed fibroblasts to cigarette smoke and have studied two important processes: oxidative stress and apoptosis.

Oxidative stress is defined as a disturbance in the oxidant-antioxidant balance, resulting in potential cell damage. It is involved in many biological and pathological processes, such as inflammation and carcinogenesis, and in the development of many pulmonary diseases (23). In response to oxidative stress, lung cells release inflammatory mediators and cytokines (TNF-α, IL-1, and IL-8) that are able to induce neutrophil recruitment and activation of transcription factors such as activator protein-1 and nuclear factor-κB (28). Apoptosis is a form of cell death that occurs under several physiological and pathological situations, and it represents a common mechanism of cell replacement, tissue remodeling, and removal of damaged cells. It is characterized by cell shrinkage, chromatin condensation, internucleosomal DNA fragmentation (18a, 24, 41), and formation of apoptotic bodies. Apoptosis may occur spontaneously or in response to specific stimuli such as heat stress, radiation, steroids, and oxidative stress. Because oxidative stress and apoptosis are implicated in numerous processes, including aging, inflammation, and carcinogenesis, it is reasonable to hypothesize a link between these two processes. The mechanisms by which oxidants can modulate the apoptotic pathways have been recently reviewed (7). The aim of this study was to evaluate the ability of cigarette smoke to induce fibroblasts oxidation and apoptosis.

MATERIALS AND METHODS

Chemicals. N-acetylcysteine (NAC) was obtained from Zambon Pharmaceutical (Vicenza, Italy), and DL-buthionine-(SR)-sulfoximine (BSO) was purchased from Sigma Chemical (Milan, Italy). Dichlorodihydrofluorescein diacetate (DCFDA) was obtained from Molecular Probes (Eugene, OR). Enzyme-linked immunosorbent assay (ELISA) kits for detection of TNF-α, IL-1, and IL-8 were obtained from R&D Systems (Minneapolis, MN). Activation of caspase-8 and caspase-9 was detected with the Apo2L/caspase-8/caspase-9 assay kit from BD Biosciences (San Diego, CA). Anti-VEGF (124), anti-tumor necrosis factor (TNF)-α (65), and anti-interleukin (IL)-8 (126) antibodies were obtained from Santa Cruz Biotechnology (Heidelberg, Germany). Anti-VEGF receptor (VEGF-R) and anti-human IL-1 receptor type 1 antibodies were obtained from R&D Systems. Anti-caspase-8 and anti-caspase-9 antibodies were obtained from Cell Signaling Technology (Danvers, MA) and Immuno-Biological Laboratories (Gottlingen, Germany), respectively. Ethidium bromide, acrylamide, Tris, sucrose, and ethylene glycol bis(2-aminoethyl ether)-N,N′-tetraacetic acid (EGTA) were obtained from Sigma Chemical. Monoclonal antibodies against phospho-ERK (Thr202/Tyr204) and total ERK were purchased from Cell Signaling Technology. N-Acetyl-DL-cysteine (NAC) was obtained from Sigma Chemical. Thiordeoxyuridine (TUDR) and mithramycin were from Calbiochem (San Diego, CA). Diisopropylfluorophosphate (DFP) and cycloheximide were from Sigma Chemical. Hydrocortisone (H9260), dexamethasone (H9251), dibutyryl cyclic AMP (H9250), and dibutyryl cyclic GMP (H9252) were from Sigma Chemical. Thiordeoxyuridine (TUDR) and mithramycin were from Calbiochem. Fetal calf serum (FCS) was obtained from Biowhittaker (Walkersville, MD).

Acknowledgments

We wish to thank Mr. L. Ferrari for his excellent technical assistance and Dr. S. Bonino for her continuous encouragement and support.

Address for reprint requests and other correspondence: S. Carnevali, Sezione di Pneumologia e Fisiopatologia Respiratoria, Dipartimento Cardio-Toracico, Via Paradisa 2, 56124 Pisa, Italia (E-mail: carnevali.stefano@unimo.it).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
etate (H2DCFDA), annexin V-FITC, propidium iodide, and Hoechst 33342 were purchased from Molecular Probe (Eugene, OR), whereas annexin V-phycocerythrin (PE) was purchased from Bender MedSystems (Vienna, Austria).

**Cell culture.** Human fetal lung fibroblasts (HFL-1, lung, diploid, human) were obtained from the American Type Culture Collection (Rockville, MD). The cells were cultured in Dulbecco’s modified Eagle’s medium (DMEM) containing 10% fetal calf serum, penicillin/streptomycin, and amphotericin B. Cultures were maintained at 37°C in a humidified atmosphere of 5% CO2. Cells were passed weekly, and cells from passages 15–20 were used for experiments.

**Preparation of cigarette smoke extract.** Cigarette smoke extract (CSE) was prepared by a modification of the method of Carp and Janoff (6). In brief, two cigarettes without filters were combusted with a modified syringe-driven apparatus. The smoke was bubbled through 50 ml of serum-free DMEM, and the resulting suspension was adjusted to pH 7.4 and then filtered through a 0.20-μm pore filter to remove bacteria and large particles. The resulting CSE was applied to fibroblast cultures within 30 min of preparation.

**Exposure to CSE**. After 3 h, the effects of the cells to 10% components of cigarette smoke, acetaldehyde and acrolein, which are present at high concentrations in cigarette smoke. In separate experiments, the cells were exposed for the same period of time as to CSE (3 h) to millimolar concentrations of acetaldehyde and micromolar concentrations of acrolein.

**Measurement of oxidative stress, apoptosis, and necrosis by cytofluorimetric analysis.** We measured cellular oxidative stress fluorometrically by monitoring the oxidation of intracellular H2DCFDA. Apoptotic cells were detected by the calcium-binding protein annexin V. In particular, phosphatidylserine residues, which are normally located in the internal phospholipid layer, are actively translocated to the external layer and thus become detectable by annexin V. Lung fibroblasts were exposed to fresh medium (control) or to different concentrations of CSE for 3 h, and, after exposure, the cells were washed twice with HBSS. H2DCFDA and annexin V were added, and cultures were then incubated for the following 20 min at 37°C. The morphological characteristics of apoptotic cells were identified with the aid of a fluorescence microscope. Cells with fragmented and/or condensed nuclei were classified as apoptotic cells.

**Single cell gel electrophoresis (Comet assay).** The alkaline single cell gel electrophoresis assay (Comet assay) was developed to assess DNA fragmentation typical of toxic DNA damage and of early-stage apoptosis (14, 15). This assay, when electrophoresis is performed at pH ≥13, provides a sensitive means of analyzing alkali-labile sites and single- and double-strand DNA breaks in small number of cells. In the electrophoretic field, DNA fragments, if present, migrate toward the anode, thus forming a comet-shaped strip. Usually, the comet tail is measured and taken as an indicator of DNA damage. Moreover, the amount of migrated DNA can be measured fluorometrically, and the product of comet tail by the percentage of migrated DNA gives an additional estimate (moment) for evaluating the total DNA damage.

In the present study, lung fibroblasts were exposed to fresh medium (control) or to 10% CSE with or without 1 mM NAC. After 3 h, the cells were trypsinized and resuspended in PBS. The assay was performed basically according to Frenzilli et al. (13). Briefly, roughened slides were cleaned with 100% methanol and air-dried. Two solutions, 0.5% normal melting agarose (NMA) and 0.7% low melting agarose (LMA) were prepared in Ca2+-, Mg2+-free PBS. For the first layer, 0.1 ml of NMA was used, whereas 85 μl of 0.7% LMA, together with 1 × 104 cells (10 μl of cell suspension plus 75 μl of LMA), were used for the second layer. Finally, a third layer of 85 μl of LMA was added. Slides were immersed in ice-cold freshly prepared lysis solution (1% sodium sarcosinate, 2.5 M NaCl, 100 mM Na2EDTA, 10 mM Tris-HCl, 1% Triton X-100, and 10% DMSO; pH 10) to lyse the cells and to allow DNA unfolding. After 1 h at 4°C in the dark, slides were placed on a horizontal electrophoresis unit. The unit was filled with fresh buffer (1 mM Na2EDTA and 300 mM NaOH, pH 13) to cover the slides. The slides were allowed to set in the high-pH buffer for 20 min to allow DNA unwinding and expression of alkali-labile sites. Electrophoresis was conducted for 20 min

Determination of oxidative stress and apoptosis at the cellular level was evaluated as previously described (21). In brief, fibroblasts were grown on gelatin-coated coverslips until they reached subconfluence. The glass coverslips were adapted to Plexiglas chambers. After exposure to CSE, HFL-1 were incubated with H2DCFDA and annexin V for 20 min at 37°C, washed twice with PBS, and observed under an inverted microscope (Nikon Eclipse TE 300) equipped with a laser confocal scanning system (Radiance Plus; Bio-Rad, Hercules, CA). The 488-nm and the 543-nm excitation wavelengths from an argon laser and the 530- and 590-nm emission filters were used to collect images from the green fluorescent probe (H2DCFDA) and the red fluorescence probe (annexin V), respectively. To minimize photo-oxidation of the probe, the laser beam was attenuated to 50% of maximal illumination, and exposure of cells to light was limited to the image acquisition intervals (2 s every 3 min) via the acquisition software. Cells were viewed with a ×60 objective lens. Control and treated dishes were scanned at the same setting parameters. Analysis of the fluorescence signal was performed with Adobe Photoshop (Adobe, San Jose, CA) for each sample, and in every experiment, the fluorescence intensity was measured by a flow cytometric assay. Flow cytometric analysis was performed with a fluorescence-activated cell sorting (FACS) Calibur flow cytometer (Becton Dickinson Immunocytometry Systems, San Jose, CA) equipped with Cell Quest analysis system. Green (for H2DCFDA) and red (for PE-annexin V) fluorescence was excited using the 488-nm line of an argon laser. Band pass filters of 530 and 585 nm were used in the experiments with H2DCFDA and annexin V, respectively, for two-color detection. The machine was optimized daily with calibrate beads (Becton-Dickinson); the amplification and the photomultiplier tube voltages were adjusted to position the beads in the predetermined scatter and fluorescence channel with compensation software. Events were collected with a suitable threshold that excluded cell debris. No initial collection window was set, and all the events were first acquired and then analyzed with Cell Quest software. A total of 10,000 events was analyzed for each sample, and in every experiment a control tube with cells alone was performed.

To distinguish between apoptosis and necrosis, in separate experiments, we exposed the cells to 10% CSE, and after double staining with annexin V-FITC (green fluorescence) and propidium iodide (red fluorescence), we analyzed the cells by FACS as previously mentioned.

**Confocal laser fluorescence microscopy.** Determination of oxidative stress and apoptosis at the cellular level was evaluated as previously described (21). In brief, fibroblasts were grown on gelatin-coated coverslips until they reached subconfluence. The glass coverslips were adapted to Plexiglas chambers. After exposure to CSE, HFL-1 were incubated with H2DCFDA and annexin V for 20 min at 37°C, washed twice with PBS, and observed under an inverted microscope (Nikon Eclipse TE 300) equipped with a laser confocal scanning system (Radiance Plus; Bio-Rad, Hercules, CA). The 488-nm and the 543-nm excitation wavelengths from an argon laser and the 530- and 590-nm emission filters were used to collect images from the green fluorescent probe (H2DCFDA) and the red fluorescence probe (annexin V), respectively. To minimize photo-oxidation of the probe, the laser beam was attenuated to 50% of maximal illumination, and exposure of cells to light was limited to the image acquisition intervals (2 s every 3 min) via the acquisition software. Cells were viewed with a ×60 objective lens. Control and treated dishes were scanned at the same setting parameters. Analysis of the fluorescence signal was performed with Adobe Photoshop (Adobe, San Jose, CA) for each sample, and in every experiment, the fluorescence intensity was measured by a flow cytometric assay. Flow cytometric analysis was performed with a fluorescence-activated cell sorting (FACS) Calibur flow cytometer (Becton Dickinson Immunocytometry Systems, San Jose, CA) equipped with Cell Quest analysis system. Green (for H2DCFDA) and red (for PE-annexin V) fluorescence was excited using the 488-nm line of an argon laser. Band pass filters of 530 and 585 nm were used in the experiments with H2DCFDA and annexin V, respectively, for two-color detection. The machine was optimized daily with calibrate beads (Becton-Dickinson); the amplification and the photomultiplier tube voltages were adjusted to position the beads in the predetermined scatter and fluorescence channel with compensation software. Events were collected with a suitable threshold that excluded cell debris. No initial collection window was set, and all the events were first acquired and then analyzed with Cell Quest software. A total of 10,000 events was analyzed for each sample, and in every experiment a control tube with cells alone was performed.

To distinguish between apoptosis and necrosis, in separate experiments, we exposed the cells to 10% CSE, and after double staining with annexin V-FITC (green fluorescence) and propidium iodide (red fluorescence), we analyzed the cells by FACS as previously mentioned.
at 25 V (300 mA). Alkali and electrophoresis treatments were performed in an ice bath. Subsequently, slides were washed gently to remove alkali and detergent in a neutralization buffer (0.4 M Tris·HCl, pH 7.5) and stained with 100 μl of ethidium bromide (2 μl/ml). All the steps described above were conducted under yellow light or in the dark to prevent additional DNA damage.

Cell GSH modulation with NAC and BSO. Because the pro-oxidant effects of CSE may be dependent on intracellular GSH concentration (25), in separate experiments we exposed fibroblasts to 10% CSE in coinubation with or without the GSH precursor NAC (1 mM). Furthermore, since BSO is known to induce GSH depletion, fibroblasts were preincubated in parallel experiments for 3 h with BSO (125 μM) and then exposed to 1% CSE with or without NAC at the same concentration used in the previous experiments. Intracellular GSH was measured on lysed cells with a commercially available assay kit (Glutathione Assay Kit; Calbiochem, San Diego, CA) according to the manufacturer’s protocol. The detection limit of the assay was 5 μM.

Statistical analysis. Results obtained by FACS were evaluated by Kolmogorov–Smirnov statistical analysis for comparisons between frequency distributions of fluorescence intensity of cells. Statistical difference between distribution of events was accepted with $D/s(n) > 8.50$.

Confocal microscopy results were expressed as fluorescence intensity/1,000 pixels, and the differences between treated cells and corresponding controls were tested with ANOVA. Statistical difference was accepted at $P < 0.05$.

Results obtained by Comet assay were evaluated by the nonparametric Kruskal-Wallis test for differences between the median values.

RESULTS

Effect of CSE. Owing to the reported CSE-induced autofluorescence in alveolar macrophages (35), we checked first whether autofluorescence due to CSE also occurred in HFL-1 cells. These experiments (triplicates) showed a slight and not significant increase of fluorescent cells after 10% CSE exposure [$D/s(n) < 8.5$] compared with unexposed cells. Moreover, cells exposed to 10% CSE and incubated with H₂DCFDA or annexin V showed a significant increase of fluorescence intensity compared with cells exposed to 10% CSE in the absence of either probes [$D/s(n) = 28.46$ and $D/s(n) = 24.01$, respectively].

FACS analysis of H₂DCFDA-labeled cells showed that treatment for 3 h of HFL-1 with various CSE concentrations (1, 5, and 10%) caused a dose-dependent increase in cellular oxidative stress. With CSE at the lowest concentration (1%) we were able to determine a slight but not significant increase in cellular oxidation (Fig. 1A), whereas the increase was statistically significant with 5% CSE [Fig. 1B, $D/s(n) = 29.08$] and with 10% CSE [Fig. 1C, $D/s(n) = 42.34$]. Similar results were obtained when cells exposed to CSE were assayed for apoptosis. The lowest dose of CSE (1%) increased cellular apoptosis, but the increase was not statistically significant (Fig. 2A). However, fibroblasts apoptosis drastically increased after exposure to 5% CSE [Fig. 2B, $D/s(n) = 33.90$] and 10% CSE [Fig. 2C, $D/s(n) = 47.39$]. Because annexin V does not discriminate between apoptotic and necrotic cells, we used propidium iodide to identify necrotic cells in three separate experiments. As shown in Fig. 3 as a representative experiment, the percentage of apoptotic cells was much greater (14.5 ± 3.9%) than necrotic cells (3.0 ± 2.2%) after exposure to 10% CSE. To verify
whether single components of CSE induce oxidative stress and apoptosis, we exposed cells to acetaldehyde (1 and 10 mM) and acrolein (10 and 100 μM). Acetaldehyde was not able to induce either oxidative stress or apoptosis at the used concentrations. However, acrolein induced both oxidative stress \[D/s(n) = 34.3\] and apoptosis \[D/s(n) = 25.4\] at high concentrations compared with controls (data not shown).

**GSH modification with NAC and BSO.** Fibroblasts were exposed for 3 h to 10% CSE with or without a concomitant nontoxic dose of NAC (1 mM). Figure 4 shows the ability of NAC to protect partially fibroblasts against the toxic effects of cigarette smoke, with a significant decrease of cellular oxidative stress [Fig. 4A, \(D/s(n) = 18.19\)]. Likewise, NAC also reduced apoptosis, as shown in Fig. 4B \(D/s(n) = 29.83\).

Because the lowest dose of CSE (1%) resulted in only a minimal increase in oxidative stress and apoptosis, we preincubated the cells for 3 h with the GSH-depleting agent BSO (125 μM) to enhance the effects of CSE. The cells were then exposed to 1% CSE with or without 1 mM NAC. Figure 5A shows that GSH depletion was able to strengthen the effect of low-dose CSE (1%) with a significant increase in cellular oxidative stress \([D/s(n) = 46.27]\). Coincubation with NAC did not completely counterbalance the effect of BSO, but a significant decrease of oxidation was detectable [Fig. 5B, \(D/s(n) = 18.58\)]. We also evaluated whether pretreatment with BSO would result in an increase of apoptosis with 1% CSE. BSO pretreatment was not able to increase the intensity of annexin V fluorescence after exposure to 1% CSE (data not shown).

The exposure to CSE was associated with a significant, dose-dependent reduction of intracellular GSH (Fig. 6). Intracellular GSH increased after coincubation with 1 mM NAC and 10% CSE (15.4 ± 1.4 μM), though not significantly, compared with 10% CSE alone (14.6 ± 2.8 μM). To the same extent, GSH content after exposure to 1% CSE (17.8 ± 4.4 μM) was reduced by BSO preincubation (14.9 ± 1.9 μM), and

![Fig. 2. Dose-response effects of CSE on apoptosis in cultured lung fibroblasts, as evaluated by flow cytometry.](http://ajplung.physiology.org/)

![Fig. 3. Human fetal lung fibroblasts (HFL)-1 treated with 10% CSE for 3 h were double stained with annexin V-FITC and propidium iodide followed by flow cytometric analysis. X-axis, annexin V-FITC fluorescence; y-axis, propidium iodide fluorescence. There was a significant higher proportion of apoptotic cells compared with necrotic cells.](http://ajplung.physiology.org/)
this effect was partially reversed by coincubation with NAC (15.6 ± 3.8 μM).

**Monitoring of oxidative stress and apoptosis by confocal laser fluorescence microscopy.** Results obtained by flow cytometry were confirmed at the single cell level (Fig. 7). As observed under light transmission microscopy, cells exposed to 10% CSE showed marked morphology changes (Fig. 7B) compared with controls (Fig. 7A). Coincubation with NAC was able to protect cells against the harmful effect of CSE (Fig. 7C), the cells looking like the controls. When we used confocal laser scanning microscopy, we observed a clear increase in fluorescence intensity, both with the oxidation probe (Fig. 7E) and with the apoptosis probe (Fig. 7H), within the cells exposed to 10% CSE compared with untreated cells (Fig. 7, D and G, respectively). It is interesting to note that the spots of red fluorescence (Fig. 7E) are present in the same cells but in different subcellular compartments from spots of green fluorescence in Fig. 7F, suggesting that oxidation and apoptosis are concomitant but distinct phenomena. Moreover, NAC was able to decrease the fluorescence intensity of both oxidative stress (Fig. 7F) and apoptosis (Fig. 7I) induced

![Graph](image1)

**Fig. 4.** Effect of N-acetylcysteine (NAC) on CSE-induced oxidative stress and apoptosis on HFL-1, as analyzed by flow cytometry. The x-axis denotes the intensity of intracellular H<sub>2</sub>DCFDA (A) or annexin V fluorescence (B). When cells were coincubated with NAC, a significant decrease of both fibroblast oxidation (A) and apoptosis (B) was obtained. A and B represent 1 of 3 separate experiments.

![Graph](image2)

**Fig. 5.** Effect of buthionine sulfoximine (BSO) pretreatment on CSE-induced lung fibroblasts oxidation, as analyzed by flow cytometry. Cells exposed to 1% CSE show a significant increase of cellular oxidative stress compared with control (A). When NAC was added to the cultures, we detected a significant decrease of cellular oxidative stress caused by BSO (B). This figure represents 1 of 3 separate experiments.

![Graph](image3)

**Fig. 6.** Dose-response effects of CSE on intracellular GSH in cultured lung fibroblasts. Significant decrease of intracellular GSH was observed in cells exposed to 5 and 10% CSE. *P < 0.05.
by CSE. After the double staining with annexin V-FITC and propidium iodide, we observed a significant accumulation of annexin V in cell membranes (Fig. 7K), whereas there was labeling with propidium iodide (Fig. 7L).

To quantify the observed differences of oxidative stress and apoptosis shown in Fig. 7, we performed a computer analysis of fluorescent signals on an equivalent region of interest, and the results were expressed as fluorescence/1,000 pixels. CSE at 10% caused a significant increase in oxidative stress (**P < 0.01, Fig. 8, solid bar) and apoptosis (**P < 0.01, Fig. 8, open bar) compared with untreated cells. Coincubation with NAC significantly decreased both cellular oxidation (***P < 0.01, Fig. 8, solid bar) and apoptosis (*P < 0.05, Fig. 8, open bar).

Detection of apoptotic cells by Hoechst 33342. Quantitative detection of apoptotic cells was performed by manual counting of Hoechst 33342-positive cells. After CSE exposure (10%), nuclear staining with Hoechst 33342, which was consistent with apoptosis, was evident in ~16% of cells, a percentage significantly different compared with nonexposed cells (Fig. 9).

DNA damage. The detection of damaged cells assessed by the Comet assay, after 3-h treatment with 10% CSE, showed a marked increase in DNA fragmentation compared with controls, as revealed by the appearance of comet-like nuclei, where the head of the comet is the unfragmented portion of DNA and the tail of the comet is the damaged DNA (Fig. 10B). The great majority of nuclei in control cells looked perfectly rounded (Fig. 10A), with only few cells showing DNA fragments moving as a comet tail. However, DNA frag-
Fibroblasts are targets for a wide variety of stimuli involved in the development of this disease (37). Previous studies support the idea that qualitative repair of pulmonary tissue might be in- destruction but also the abnormal quantitative and development of pulmonary emphysema, it is possible that not only the involvement in the development of pulmonary emphysema (6, 36). However, since only some 15% of smokers develop emphysema, it is possible that not only the but also the abnormal quantitative and qualitative repair of pulmonary tissue might be involved in the development of this disease (37).

Fibroblasts are the main cell type in connective tissue, and they play a major role in the repair of pulmonary tissue. Previous studies support the idea that fibroblasts are targets for a wide variety of stimuli including cigarette smoke. For instance, cigarette smoke was able to inhibit fibroblast recruitment and proliferation (26) and to alter fibroblast-mediated collagen gel contraction in vitro (5). We used a human lung fibroblast cell line as a model to study some of the harmful effects of cigarette smoke. In this study, we showed that cigarette smoke is able to induce cellular oxidative stress and that the oxidation depends on the concentrations of CSE. We also demonstrated that cigarette smoke induces fibroblast apoptosis that parallels the oxidation, possibly because direct cigarette smoke oxidants and/or intracellular reactive oxygen species (ROS) generated by cigarette smoke can switch on apoptotic pathway(s) in fibroblasts. Assessment of apoptosis in our experiments was based on annexin V labeling and nuclear staining with Hoechst 33342. DNA fragmentation, which is involved in the development of programmed cell death as a part of total CSE-induced DNA damage, was studied by the Comet assay.

The Comet assay is currently used to show DNA fragmentation (30) to such an extent that warnings on the use of Comet assay as an indicator of genotoxic damage when apoptosis may also occur have been recently published (8). The oxidative and proapoptotic effects of cigarette smoke exposure on HFL-1 cells begin at very low CSE concentrations (1%) and reach statistical significance against controls at 5% concentration just after 3 h of incubation. This suggests that fibroblasts in the lung interstitium of smokers may be continuously challenged by compounds capable of interfering with their functions and/or lifespan. We speculate that the concomitant oxidation and apoptosis in human lung fibroblasts we observed in vitro after short-term exposure to CSE may lead, when repeated thousands of times in a smoker’s life, to a defective tissue repair and contribute to the development of

### DISCUSSION

Cigarette smoke is known to induce oxidative stress and inflammation in pulmonary tissues and cells, both in vitro and in vivo. It contains over 4,000 chemical species, including high concentrations of oxidants (9). The imbalance between oxidants and antioxidants is involved in the development of pulmonary emphysema (6, 36). However, since only some 15% of smokers develop emphysema, it is possible that not only the fibroblast-mediated collagen gel contraction (5). We used a human lung fibroblast cell line as a model to study some of the harmful effects of cigarette smoke. In this study, we showed that cigarette smoke is able to induce cellular oxidative stress and that the oxidation depends on the concentrations of CSE. We also demonstrated that cigarette smoke induces fibroblast apoptosis that parallels the oxidation, possibly because direct cigarette smoke oxidants and/or intracellular reactive oxygen species (ROS) generated by cigarette smoke can switch on apoptotic pathway(s) in fibroblasts. Assessment of apoptosis in our experiments was based on annexin V labeling and nuclear staining with Hoechst 33342. DNA fragmentation, which is involved in the development of programmed cell death as a part of total CSE-induced DNA damage, was studied by the Comet assay.

The Comet assay is currently used to show DNA fragmentation (30) to such an extent that warnings on the use of Comet assay as an indicator of genotoxic damage when apoptosis may also occur have been recently published (8). The oxidative and proapoptotic effects of cigarette smoke exposure on HFL-1 cells begin at very low CSE concentrations (1%) and reach statistical significance against controls at 5% concentration just after 3 h of incubation. This suggests that fibroblasts in the lung interstitium of smokers may be continuously challenged by compounds capable of interfering with their functions and/or lifespan. We speculate that the concomitant oxidation and apoptosis in human lung fibroblasts we observed in vitro after short-term exposure to CSE may lead, when repeated thousands of times in a smoker’s life, to a defective tissue repair and contribute to the development of

### Table 1. Induction of DNA damage by cigarette smoke

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tail Length, μm</th>
<th>Tail Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.5 ± 10.3</td>
<td>7.3 ± 35.2</td>
</tr>
<tr>
<td>10% CSE</td>
<td>40.3 ± 16.8*</td>
<td>614.1 ± 742.3*</td>
</tr>
<tr>
<td>10% CSE + NAC</td>
<td>2.8 ± 8.0</td>
<td>3.2 ± 10.8</td>
</tr>
</tbody>
</table>

Values are mean ± SE. Analysis by Kruskal-Wallis test shows a significant increase of tail length and tail moment when cells were exposed to 10% cigarette smoke extract (CSE) (*P < 0.01). N-acetylcysteine (NAC) abolished completely the effect of CSE with tail length and moment in the same order of magnitude of controls.
CSE INDUCES OXIDATIVE STRESS AND APOPTOSIS

L962

pulmonary emphysema (31). The negative effect of CSE on fibroblast functions due to oxidation (26) may further hamper the efficacy of tissue repair. The increase of apoptotic changes, as revealed by the attachment of annexin V to the outer layer of the cell membrane of HFL-1 cells, occurred in our study just 3 h after CSE exposure. This is in agreement with very recent observations from Jungas and colleagues (17), who demonstrated activation of Bax 4 h after exposure of HeLa cells to \( \text{H}_2\text{O}_2 \).

We also evaluated the efficacy of GSH modification to modulate the toxic effects of cigarette smoke on human lung fibroblasts. To this end, we first used NAC, a potent antioxidant agent showing protective effects in several models of lung injury (3, 40), to enhance intracellular GSH content by increasing cysteine supply (10). NAC can also block apoptosis induced by different agents (32), and the protective effect of NAC in nicotine-induced apoptosis in rat gingival fibroblasts has been reported (19).

In our experiments NAC was able to reduce the toxic effects of cigarette smoke with a significant and parallel decrease of both oxidative stress and apoptosis. These results lend further support to the hypothesis that cellular oxidative stress and apoptosis induced by cigarette smoke are closely related each other. Moreover, it is known that depletion of GSH can drastically reduce the defenses against oxidant-induced lung injury (25), and it also causes an increase of apoptotic cells (22). We then used a GSH-depleting agent such as BSO to modify intracellular GSH (4, 11, 12). Depletion of GSH caused by BSO significantly enhanced the effect of low doses of CSE. In fact, although 1% CSE resulted in only a slight increase of oxidative stress in fibroblasts, cellular oxidation dramatically increased when cells were preincubated with BSO. Depletion of GSH, together with ROS production, has been also suggested to be involved in apoptosis (12), and depletion of cellular thiols is known to induce apoptosis in T cells and fibroblasts (1, 33). Coincubation of HFL-1 with 1 mM NAC did not completely correct the 10% CSE-induced GSH depletion. Similarly, NAC did not reverse the BSO- and 1% CSE-induced GSH depletion, suggesting that the observed antioxidant effect of NAC may be due, at least in part, to a direct scavenging effect on CSE-derived oxidant radicals. Altogether, these results expand very recent observations by Ishii and coworkers (16), by showing that the proapoptotic influence of CSE on HFL-1 cells is associated with cell oxidation and that these effects can be observed as early as 3 h after CSE exposure.

These results support recent findings on the importance of resident cells in the development of emphysema. In a recent paper (18), cigarette smoke has been reported to alter VEGF maintenance of pulmonary endothelial cells, and this may result in emphysema due to pulmonary endothelial cell death, followed by progressive disappearance of the alveolar septa by apoptosis. This model of emphysema does not appear to involve inflammatory cells, and it indicates that parenchymal lung cells may enter a death cycle in emphysema before the actual damage to the parenchymal extracellular matrix. In this study, we demonstrated that fibroblasts undergo apoptosis after exposure to cigarette smoke, which parallels the increase in oxidative stress. We speculate that the development of pulmonary emphysema might be not only the result of an imbalance between oxidants and antioxidants, and/or between proteases and antiproteases, but also the consequence of fibroblast oxidation and apoptosis caused by cigarette smoke. Moreover, the protective effect of antioxidants such as NAC against the toxic effects of cigarette smoke underlines the importance of this class of molecules in the treatment of tobacco smoke-induced pulmonary diseases.

This work was supported in part by funds from Ministero dell’ Università e della Ricerca Scientifica - Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale, 1999 (No. 9906242433).

REFERENCES

15. Godard T, Deslandes E, Lebaillly P, Vigeaux C, Sichel F, Poul JM, and Gauduchon P. Early detection of staurosporine-


