ORIGINAL ARTICLE

Increased ectodomain shedding of lung epithelial cell adhesion molecule 1 as a cause of increased alveolar cell apoptosis in emphysema

Takahiro Mimae,1,2 Man Hagiyama,3 Takao Inoue,3 Azusa Yoneshige,3 Takashi Kato,3 Morihito Okada,1 Yoshinori Murakami,2 Akihiko Ito3

ABSTRACT
Rationale Alveolar epithelial cell apoptosis and protease/antiprotease imbalance based proteolysis play central roles in the pathogenesis of pulmonary emphysema but molecular mechanisms underlying these two events are not yet clearly understood. Cell adhesion molecule 1 (CADM1) is a lung epithelial cell adhesion molecule in the immunoglobulin superfamily. It generates two membrane associated C terminal fragments (CTFs), αCTF and βCTF, through protease mediated ectodomain shedding.

Objective To explore the hypothesis that more CADM1-CTFs are generated in emphysematous lungs through enhanced ectodomain shedding, and cause increased apoptosis of alveolar epithelial cells.

Methods and results Western blot analyses revealed that CADM1-CTFs increased in human emphysematous lungs in association with increased ectodomain shedding. Increased apoptosis of alveolar epithelial cells in emphysematous lungs was confirmed by terminal deoxynucleotidyl nick end labelling (TUNEL) assays. NCI-H441 lung epithelial cells expressing mature CADM1 but not CTFs were induced to express αCTF both endogenously (by shedding inducers phorbol ester and trypsin) and exogenously (by transfection). Cell fractionation, immunofluorescence, mitochondrial membrane potential, JC-1 dye labelling and TUNEL assays revealed that CADM1-αCTF was localised to mitochondria where it decreased mitochondrial membrane potential and increased cell apoptosis. A mutation in the intracytoplasmic domain abrogated all three abilities of αCTF.

Conclusions CADM1 ectodomain shedding appeared to cause alveolar cell apoptosis in emphysematous lungs by producing αCTF that accumulated in mitochondria. These data link proteolysis to apoptosis, which are two landmark events in emphysema.

INTRODUCTION
Emphysema is a pulmonary disease characterised by alveolar wall destruction, resulting in enlarged airspaces and loss of surface area for gas exchange without fibrosis.1 This unique aspect of alveolar destruction has long been ascribed mainly to excessive apoptosis of alveolar structural (non-inflammatory) cells (ie, epithelial and endothelial cells), and a relative excess of proteases causing a local imbalance between pro- and antiproteases.2,3 Apoptosis of endothelial cells in the alveolar wall is well explained by two mechanisms: decreased maintenance signals for endothelial cells mediated through vascular endothelial growth factor and its cognate receptor, and increased proteolysis of extracellular matrices in the alveolar wall resulting from a protease/antiprotease imbalance.3,4 However, the molecular basis for alveolar epithelial cell apoptosis specific to emphysema is not yet fully understood. Involvement of a protease/antiprotease imbalance has generally been speculated because degradation of the extracellular matrix caused by excessive proteases forces alveolar cells to fall into anoikis, a type of programmed cell death, secondary to cell detachment from the matrix.4 However, studies over the past decade have suggested that alveolar epithelial destruction in emphysematous lungs might occur due to apoptosis, possibly unrelated to matrix degradation induced by proteases. An in vitro experiment showed that leucocyte elastase induces apoptosis in lung epithelial cells by changing mitochondrial permeability, mediated by a protease activated receptor 1 triggered pathway.
involved activation of nuclear factor κB and p53. Cathepsin S, a cysteine protease secreted from pulmonary macrophages, mediates alveolar epithelial cell apoptosis in interferon γ induced emphysema of mice by activating both mitochondrial and death receptor pathways. Matrix metalloproteinases trigger activation of the death receptor apoptotic pathway by processing the tumour necrosis factor α precursor and Fas ligand to yield their bioactive forms. These results suggest that excessive proteases can directly act on alveolar epithelial cells and cause apoptosis, but this possibility has not been intensively examined.

Cell adhesion molecule 1 (CADM1), also widely known as tumour suppressor in lung cancer 1 (TSLC1), is an intercellular adhesion molecule in the immunoglobulin superfamily. It is a membrane spanning glycoprotein composed of three extracellular immunoglobulin-like domains, a single transmembrane region and a short cytoplasmic tail with a transmembrane-type II domain and a PDZ type II domain interaction sequence and a PDZ type II domain binding motif. CADM1 localises to the lateral plasma membrane in pulmonary and biliary epithelia and binds trans-homophilically between adjacent cells. Consequently, it is assumed to contribute to the integrity of epithelial cell structure and polarity. Recent studies by our own and other laboratories have revealed that CADM1 expression is regulated by post-transcriptional mechanisms, including glycosylation and proteolytic cleavage, called shedding.

The tumour necrosis factor α (ie, CTFs and ICD) have any biological function. Although we previously proposed CADM1 shedding as a candidate mechanism for downregulating full-length CADM1, it remains unknown whether the products generated by shedding (ie, CTFs and ICD) have any biological function.

In the present study, we compared CADM1 expression between emphysematous and normal lungs and found that αCTF and βCTF increased in emphysematous lungs in association with increased ectodomain shedding of CADM1. Because alveolar cell apoptosis also increased in emphysematous lungs, we then examined the possible association between CADM1 ectodomain shedding and alveolar cell apoptosis. Human lung epithelial cells were induced to express endogenous αCTF by shedding inducers and were transfected to express exogenous αCTF. Cell fractionation and immunofluorescence experiments revealed that αCTF localised to mitochondria. This localisation appeared to result in mitochondrial depolarisation and induction of cell apoptosis. These data identify CADM1-αCTF as a key molecule that links two landmark events in emphysema, proteolysis and apoptosis.

**Table 1 Clinical characteristics of patients with normal and emphysematous lungs**

<table>
<thead>
<tr>
<th>Case</th>
<th>Normal (non-smoker)</th>
<th>Normal (smoker)</th>
<th>Emphysema (smoker)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  2  3  4  5</td>
<td>6  7  8  9  10</td>
<td>11  12  13  14  15  16  17  18  19  20  21</td>
</tr>
<tr>
<td>Age (years)</td>
<td>64  50  48  63  76</td>
<td>60  56  80  71  84</td>
<td>79  62  62  68  76  58  80  70  70  84  79</td>
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<tr>
<td>Sex</td>
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<td>M  F  M  M  M</td>
<td>M  M  M  M  M  F  F  M  M  M</td>
</tr>
<tr>
<td>Brinkman Index</td>
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<td>2220  980  800  1600  1600  1000  600  200  1000  1280  1200</td>
</tr>
<tr>
<td>Cause of surgery</td>
<td>AD  AD  AD  AD  AD</td>
<td>AD  AD  AD  SCLC  AD  AD  AD  AD  AD  AD  AD  AD  AD  SCLC  CH  CH  CH  AD</td>
<td></td>
</tr>
<tr>
<td>Excised lung lobe*</td>
<td>RR  RU  RU  RL  LL</td>
<td>RU  RL  RU  RL  LL  LU  RU  RU  RU  LU  RU  RL  RM  RU  RL</td>
<td></td>
</tr>
<tr>
<td>FEV1/FVC</td>
<td>82.3  80.5  86.6  86.8  79.9</td>
<td>73.0  76.7  76.6  76.8  81.4</td>
<td>84.1  61.7  73.2  75.1  55.0  88.8  78.1  74.6  76.7  73.0  83.5  61.5</td>
</tr>
<tr>
<td>Tlco (%)</td>
<td>101.8  92.8  76.5  49.3</td>
<td>102.0  81.2  57.0  41.2  89.3</td>
<td>37.8  37.8  51.2  44.4  36.8  55.3  54.8  53.0  36.3  68.2</td>
</tr>
</tbody>
</table>

AD, adenosccarcinoma; CH, chondroid hamartoma; FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; NE, not examined; PC, pleomorphic carcinoma; SCLC, small cell lung carcinoma; SQ, squamous cell carcinoma; Tlco, carbon monoxide transfer factor.

*LL, left lower; LU, left upper; RL, right lower; RM, right middle; RU, right upper.
In contrast, expression levels of αCTF and βCTF increased significantly in emphysematous lungs, while they were comparable between smokers and non-smokers with normal lungs (figure 1B). We also calculated the signal intensity ratios of αCTF and βCTF to the full length form for each case, and found that these ratios were significantly higher in emphysematous lungs than those in normal lungs (figure 1C), and were strongly positively correlated with αCTF and βCTF levels ($R^2=0.952$ and $0.877$; $p<0.001$), respectively (figure 1D). The ratios of the two shed forms were comparable between smokers and non-smokers with normal lungs. These results indicate that CADM1 ectodomain shedding was
accelerated to generate more αCTF and βCTF in emphysematous lungs.

**Increased apoptosis of alveolar cells in emphysematous lungs**

Lung sections were double stained by the terminal deoxynucleotidyl transferase mediated dUTP nick end labelling (TUNEL; green) and E-cadherin immunofluorescence (red) (figure 2A, B). Alveolar epithelial cells were identified by membranous staining for E-cadherin. Practically all alveolar cells were TUNEL negative in normal lungs, irrespective of smoking habit, whereas >10% of alveolar cells on average were TUNEL positive in emphysematous lungs (p<0.002) (figure 2C).

**CADM1-αCTF localises to mitochondria**

To probe for a possible link between increased CADM1 ectodomain shedding and increased alveolar cell apoptosis, we used NCI-H441 cells, a human lung epithelial cell line with characteristics of Clara cells. Western blot analyses detected abundant expression of the full length form of CADM1 in NCI-H441 cells grown under standard culture conditions, but the two shed forms αCTF and βCTF were undetectable, indicating that CADM1 was rarely shed in steady state NCI-H441 cells. We used phorbol 12-myristate 13-acetate (PMA) and trypsin to induce CADM1 shedding, which both induce ectodomain shedding of transmembrane proteins. When the cells were treated with a mixture of PMA (200 nM) and trypsin (0.0125% w/v, a concentration low enough to prevent cell detachment) for 20 min, but not with either alone, a considerable amount of αCTF appeared with a slight decrease in the amount of full length CADM1, indicating that CADM1 ectodomain shedding was induced by the treatment (figure 3). The reason why βCTF was not produced by the treatment is unknown. Considering that β shedding of β-amyloid precursor protein, a key event in Alzheimer’s disease, occurs within cells, trypsin may have no potential to activate β shedding due to its inaccessibility to β-sheddase(s).

PMA and trypsin treated or untreated cells were then double stained by CADM1 immunofluorescence and Mitotracker dye, a mitochondrial marker. CADM1 immunostaining was exclusively

![Figure 2](http://thorax.bmj.com/)
Induction of cell adhesion molecule 1 (CADM1) ectodomain shedding and exogenous expression of αCTF and αCTFmut in NCI-H441 cells. NCI-H441 cells were treated with either phorbol myristic acid (PMA 200 nM) or trypsin (0.0125% w/v), or a mixture of both, or were transfected with pCX4bsr-SP-αCTF, pCX4bsr-SP-αCTFmut or an empty vector. After 20 min of treatment and 2 days of transfection, the cells were subjected to western blot analyses with the CADM1 antibody.

detected on the cell membrane of untreated cells (figure 4Aa), whereas PMA and trypsin treatment resulted in a marked appearance of cytoplasmic stains for CADM1, which were significantly colocalised with Mitotracker stain (figure 4Ab, B), suggesting subcellular localisation of CADM1-αCTF to mitochondria.

We examined this possibility by expressing αCTF exogenously. Because CADM1 ectodomain shedding likely occurs on the cell surface,14 αCTF should be primarily a transmembrane protein. Thus according to our previous mass spectrometric data that determined the N terminal amino acid residue of αCTF,14 we constructed a plasmid vector expressing a large deletion form of CADM1, in which the signal peptide was ligated upstream of the ΔCTF (pCX4bsr-SP-αCTF). We mutated the intracytoplasmic domain of αCTF as a control so that the resulting domain would not target to mitochondria but to the cytosol (pCX4bsr-SP-αCTFmut; online supplementary figure S3), according to an intracellular localisation prediction algorithm (WoLF PSORT; refer to online supplementary methods). We transfected NCI-H441 cells with either plasmid construct, and 2 days later confirmed that the transfectants expressed a considerable amount of exogenous αCTF or αCTFmut by western blot analyses (figure 3). The ratios of αCTF to full length CADM1 in transfectants were equivalent to those in emphysematous lungs (see online supplementary figure S4). Taken together with the western blot results indicating that endogenous full length CADM1 in NCI-H441 cells was certainly lower than that in normal lung epithelial cells in vivo (see online supplementary figure S4), transfectants with pCX4bsr-SP-αCTF were considered to resemble epithelial cells from emphysematous lungs rather than normal lungs, in terms of CADM1 protein levels.

NCI-H441 transfectants were double stained with CADM1 immunofluorescence and Mitotracker dye. Transfectants with pCX4bsr-SP-αCTF exhibited a staining pattern quite similar to that of PMA and trypsin treated cells; the cytoplasmic CADM1 signals were well colocalised with Mitotracker stain (figure 4Ac, B). In contrast, pCX4bsr-SP-αCTFmut transfectants showed a strong CADM1 membranous staining with weak but significant cytoplasmic signals that were rarely colocalised with Mitotracker stain (figure 4Ad, B).

Mitochondrial localisation of αCTF was examined by cell fractionation of NCI-H441 cells expressing endogenous and exogenous αCTF. Exogenous αCTF and αCTFmut were expressed as N terminally FLAG tagged forms to clearly distinguish them from endogenous αCTF using the p3xFLAG-CMV-9 vector, which is designed to deliver the protein encoded by the cDNA insert efficiently to the cell surface. Expression of FLAG tagged proteins was confirmed by western blotting with an anti-FLAG antibody (see online supplementary figure S5). Transfected or untransfected NCI-H441 cells were treated with a mixture of PMA (200 nM) and trypsin (0.25% w/v) for 20 min to induce endogenous αCTF and detach cells without mitochondrial damage and then were fractionated into cytosolic and mitochondrial fractions. Whole cytoplasmic lysates without nuclei were also prepared from aliquots of the treated cells. Successful fractionation was verified by western blotting analyses, showing enrichment of glyceraldehyde 3-phosphate dehydrogenase (G3PDH), a cytosolic marker, and cytochrome c oxidase subunit IV (CoxIV), a mitochondrial marker, in the corresponding fractions (figure 5). Reprobing with the CADM1 antibody revealed that both endogenous and exogenous αCTFs were detected exclusively in the mitochondrial fraction as CoxIV whereas αCTFmut was enriched in the cytosolic fraction as greatly as G3PDH (figure 5).

Lung sections were double stained with antibodies against CADM1 and mitochondria. CADM1 immunostaining in alveolar epithelial cells was primarily membranous in normal lungs whereas it was occasionally both membranous and cytoplasmic in emphysematous lungs and cytoplasmic staining was appreciably colocalised with mitochondrial staining (figure 2D). The proportion of epithelial cells with this colocalisation signal was significantly larger in emphysematous lungs (n=4) than in normal lungs (n=4) (11.3±8.3 vs 1.8±1.5%; p=0.038).

### CADM1-αCTF decreases mitochondrial membrane potential and induces apoptosis

We examined whether CADM1-αCTF might alter mitochondrial membrane potential (ΔΨm) that normally exists across the inner mitochondrial membrane using the JC-1 probe, a lipophilic cationic dye that exhibits ΔΨm dependent accumulation in mitochondria, as indicated by a fluorescence shift from green (≈525 nm) to red (≈590 nm). NCI-H441 transfectants expressing exogenous αCTF or αCTFmut were stained with JC-1 dye at 24, 48 and 72 h post-transfection, and mitochondrial depolarisation was assessed by measuring the red/green fluorescence intensity ratio of the dye (figure 6A and see online supplementary figure S6). αCTFmut did not change the JC-1 ratio at any time point, whereas αCTF significantly decreased the ratio at 48 and 72 h (figure 6B). Transfected and untransfected NCI-H441 cells were stained by the TUNEL technique 48 h after transfection. αCTFmut did not change the proportion...
Figure 4  Immunoﬂuorescence of cell adhesion molecule 1 (CADM1) with Mitotracker staining in NCI-H441 cells expressing α C terminal fragment (CTF) and αCTFmut. (A) NCI-H441 cells were untreated (a) or treated with a mixture of phorbol myristic acid and trypsin (b), or were transfected with pCX4bsr-SP-αCTF (c) or pCX4bsr-SP-αCTFmut (d). Then, cells were double stained with CADM1 immunoﬂuorescence (green; left) and Mitotracker ﬂuorescence (red; middle). In the merged images (right), yellow areas mean colocalisation of both ﬂuorescent signals—that is, mitochondrial localisation of CADM1. Bar=10 μm. (B) Graph showing overlap coefﬁcients in NCI-H441 cells of the four types (a–d shown in (A)). Intensity correlation between green and red ﬂuorescence was quantiﬁed using ImageJ Colocalisation Analysis, and overlap coefﬁcients were calculated. Data are expressed as mean±SD, and statistical signiﬁcance was analysed by the Student’s t test. *p<0.01 compared with the value of untreated cells (a in (A)).

of TUNEL positive cells whereas αCTF increased the proportion fivefold (p<0.01) (figure 6B).

**DISCUSSION**

We found that CADM1 ectodomain shedding increased in emphysematous lungs from smoking patients, but not in normal lungs from smoking patients, suggesting that oxidants in cigarette smoke may act as a critical inducer of CADM1 ectodomain shedding only in subjects who have particular genetic backgrounds. Of interest, changes in emphysema susceptible genes, such as α-1 antitrypsin, macrophage elastase, klotho and surfactant D, lead to a relative excess of proteases, creating a local protease/antiprotease imbalance. Although mechanisms underlying these events remain largely unknown, clathrin mediated endocytosis is shown to be involved. After internalisation, mucin 1 is assumed to utilise heat shock proteins as molecular chaperons for mitochondrial translocation. Higashiyama et al demonstrated that the remnant peptides generated by ectodomain shedding of type I integral membrane proteins, such as pro-heparin binding epidermal growth factor-like growth factor and pro-amphiregulin, are internalised into endocytotic vesicles. The N and C termini of the peptides are positioned inside and outside of the vesicles, respectively, and the C terminal tail, free in the cytosol, plays a decisive role in the intracellular destinations of the remnant peptide. αCTF may be present as a vesicle associated transmembrane molecule in the cytoplasm, with its C terminal tail being free outside the vesicle, and this C terminal tail may carry a conformational signal that serves as a binding site for molecular chaperons, such as heat shock protein family members.

Exogenous αCTF decreased mitochondrial membrane potential in NCI-H441 cells and increased apoptosis, suggesting that mitochondrial localisation of αCTF might result in activation of the mitochondrial apoptosis pathway. Mao et al reported that exogenous CADM1 induces caspase 3 activation and apoptosis in A549 lung adenocarcinoma cells lacking endogenous CADM1, and that protein 4.1 binding motif and PDZ domain binding motif in the intracytoplasmic domain are indispensable for this induction. Members of the membrane associated guanylate kinase (MAGuK) family are known as binding partners to the latter motif. Interestingly, this family contains a subgroup that carries the caspase recruitment domain in its N terminal.

**Figure 5** Cell fractionation experiments of NCI-H441 cells expressing α C terminal fragment (CTF) and αCTFmut. NCI-H441 cells were untransfected (left) or transfected with p3xFLAG-αCTF (middle) or p3xFLAG-αCTFmut (right), and were fractionated into cytosolic (CS) and mitochondrial (Mit) fractions. Whole cytoplasmic lysates (CP) were extracted from aliquots of the cells. These lysates and fractions were analysed with western blotting using antibodies against cell adhesion molecule 1 (CADM1), cytochrome c oxidase subunit IV (CoxIV) and glyceraldehyde 3-phosphate dehydrogenase (G3PDH). Open and closed arrows indicate FLAG tagged αCTF and αCTFmut, respectively.
region and participates in apoptosis signalling. αCTF and βCTF, which both share the intracytoplasmic domain, once produced, may activate the mitochondrial apoptosis pathway by transporting particular MAGuK family members to mitochondria in alveolar epithelial cells. 

There are several splice variants of human CADM1, named isoforms SP1 to SP4. Reverse transcription-PCR revealed that nine lungs examined and NCI-H441 cells all expressed SP4 exclusively (see online supplementary figure S8). Tanabe et al showed that SP1 and SP2 are shed constitutively, while SP3 is non-cleavable. Our data proved SP4 cleavable. SP4 ectodomain shedding appeared to be not constitutive but induced by particular pathological stimuli. Moiseeva et al reported that SP4 overexpressing HMC-1 mast cells show better survival and lower caspase 3/7 activity than SP1 overexpressing cells. This difference between two isoforms may be explained by their distinct susceptibility to ectodomain shedding. In HMC-1 cells, SP1 may produce more αCTF and/or βCTF than SP4, resulting in activation of the mitochondrial apoptosis pathway.

In conclusion, we propose increased ectodomain shedding of CADM1 as a novel molecular mechanism for increased alveolar cell apoptosis in emphysematous lungs. This mechanism is an extension of the conventional understanding that proteolytic activity is locally excessive in emphysematous lung alveoli because CADM1 ectodomain shedding per se is a proteolytic process, and also suggests that selective inhibitors to block CADM1 sheddase activity and/or mitochondrial localisation of CADM1 shedding products can slow or halt the progression of emphysema. In fact, ADAM10 is released by human alveolar macrophages, and intratracheal administration of an adenoviral vector expressing ADAM10 in mice results in the development of emphysema. Further characterisation of CADM1 ectodomain shedding and its associated molecular events will open a new avenue for target based therapeutic approaches to emphysema.

Contributors AI and YM designed the study, and AI wrote the manuscript. AI, TM and MO provided the clinical samples. TM, MH, TI, AY and TK performed the experiments, and MH analysed the data.
Chronic obstructive pulmonary disease

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Competing interests None.

Patient consent Obtained.

Ethics approval Ethics approval was provided by the ethics committee of Hiroshima University and Kinki University, Japan (approval Nos Eki-350 and 25–088).

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REFERENCES


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