

NADPH oxidase DUOX1 sustains TGF-β1 signalling and promotes lung fibrosis

Ruy Andrade Louzada, Raphaël Corre, Rabii Ameziane El Hassani, Lydia Meziani, Madeleine Jaillet, Aurélie Cazes, Bruno Crestani, Eric Deutsch, Corinne Dupuy

▶ **To cite this version:**

Ruy Andrade Louzada, Raphaël Corre, Rabii Ameziane El Hassani, Lydia Meziani, Madeleine Jaillet, et al.. NADPH oxidase DUOX1 sustains TGF-β1 signalling and promotes lung fibrosis. European Respiratory Journal, 2021, 57 (1), pp.1901949. 10.1183/13993003.01949-2019 . hal-03445788

HAL Id: hal-03445788
https://cnrs.hal.science/hal-03445788

Submitted on 25 Nov 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

NADPH oxidase DUOX1 sustains TGF-β1 signalling and promotes lung fibrosis

Ruy Andrade Louzada[1], Raphaël Corre[1], Rabii Ameziane El Hassani[2], Lydia Meziani[3], Madeleine Jaillet[4], Aurélie Cazes[5], Bruno Crestani[4,6], Eric Deutsch[3]and Corinne Dupuy[1].

Affiliations : [1]CNRS UMR 8200, Université Paris-Saclay, Gustave Roussy, Villejuif, France. [2]Laboratoire de Biologie des Pathologies Humaines, Université Mohammed V, Faculté des Sciences, Rabat, Morocco. [3]Inserm U1030, Université Paris-Saclay, Gustave Roussy, [4]INSERM U1152, Paris, France. [5]Département de Pathologie, Hôpital Bichat, Paris, France. [6]Université Paris-Diderot, LABEX INFLAMEX, Paris, France. Assistance Publique-Hôpitaux de Paris, DHU FIRE, Hôpital Bichat, Paris, France.

Correspondence : Corinne Dupuy, Gustave Roussy, UMR 8200 CNRS, 114 rue Edouard Vaillant ; 94805 Villejuif, France. Email: corinne.dupuy@gustaveroussy.fr

Abstract (250)

Interstitial lung fibroblast activation coupled with extracellular matrix production is a pathological signature of pulmonary fibrosis, and is governed by transforming growth factor (TGF-β1) /Smad signalling. TGF-β1 and oxidative stress cooperate to drive fibrosis**.** Cells can produce reactive oxygen species (ROS) through activation and/or induction of NADPH oxidases, such as dual oxidase (DUOX1/2). Since DUOX enzymes, as extracellular H_2O_2-generating systems, are involved in extracellular matrix formation and in wound healing in different experimental models, we hypothesized that DUOX-based NADPH oxidase plays a role in the pathophysiology of pulmonary fibrosis.

Our *in vivo* data (IPF patients and mouse models of lung fibrosis) showed that the NADPH oxidase DUOX1 is induced in response to lung injury. DUOX1-deficient mice (DUOX1+/- and DUOX-/-) had an attenuated fibrotic phenotype. In addition to being highly expressed at the epithelial surface of airways, DUOX1 appears to be also well expressed in the fibroblastic foci of remodelled lungs. By using primary human and mouse lung fibroblasts, we showed that TGF-β1 upregulates DUOX1 and its maturation factor DUOXA1 and that DUOX1-derived H_2O_2 promoted the duration of TGF-β1-activated Smad3 phosphorylation by preventing phospho-Smad3 degradation. Analysis of the mechanism revealed that DUOX1 inhibited the interaction between phospho-Smad3 and the ubiquitin ligase NEDD4L, preventing NEDD4L-mediated ubiquitination of phospho-Smad3 and its targeting for degradation.

These findings highlight a role for DUOX1-derived H_2O_2 in a positive feedback that amplifies the signalling output of the TGF-β1 pathway and identify DUOX1 as a new therapeutic target in pulmonary fibrosis.

Introduction (332 words)

Lung fibrosis is characterized by excessive matrix deposition leading to the destruction of lung architecture and ultimately fatal impairment of lung function [1]. Lung fibrosis is currently irreversible and refractory to treatment. It may develop secondarily to an insult (inhalation of foreign particles, radiation, chronic hypersensitivity, etc.) [2]. One of the hurdles to developing therapeutics is a lack of complete understanding of the molecular mechanisms underlying the pathogenesis of the disease. Persistence of activation/differentiation of the fibroblasts into myofibroblasts, which is controlled in particular through TGF-β1 signalling, contribute to the development of fibrosis. A growing body of evidence supports the hypothesis that an oxidant-antioxidant imbalance with consequent chronic oxidative stress might drive the progression of fibrosis [3, 4]. Under some pathological conditions, reactive oxygen species (ROS) production is greatly increased causing oxidative stress, which is responsible for severe tissue lesions. ROS and markers of oxidative stress are evident in human idiopathic pulmonary fibrosis (IPF), and levels of ROS negatively correlate with pulmonary function in IPF and may predict disease severity [5-7]. Cells can produce ROS through activation and/or induction of NADPH oxidases (NOX), which constitute a family of enzymes that are expressed in different cell locations and have specific functions [8]. The NOX family consists of seven members, five NOXs (NOX1-5) and two dual oxidases (DUOX1/2). NOX4 has been associated with IPF pathophysiology and is currently a target for antifibrotic molecules development [9, 10]. Initially identified in the thyroid [11,12], DUOXs are also well expressed in the airway surface epithelium where they participate in innate defence [13]. Since DUOX enzymes, as extracellular H_2O_2-generating systems, are involved in extracellular matrix formation and in wound healing in different experimental models [14, 15], we hypothesized that DUOX-based NADPH oxidase plays a role in the pathophysiology of pulmonary fibrosis. For the first time, we found that DUOX1 but not DUOX2 was induced in fibroblasts in response to lung injury and that DUOX1-derived H_2O_2 promoted the duration of TGF-β1 signalling in these cells by preventing phospho-Smad3 degradation.

Material and methods (351 words)

Detailed methods are available in the online supplementary material

Subjects

IPF lung samples were obtained from patients undergoing open lung biopsy or at the time of lung transplantation (*n* =10; median age 58 yr; range 50–64 yr). IPF was diagnosed according to 2011 ATS/ERS/JRS/ALAT criteria, including histopathological features of usual interstitial pneumonia [16]. Lung samples obtained after cancer surgery, away from the tumor, were used as controls; normalcy of control lungs was verified histologically (*n* =10 patients; median age 62 yr, range 44–81 yr).

Lung tissue samples were used for qRT-PCR analysis of DUOX2 and DUOX1 expression, Human primary pulmonary fibroblasts were cultured cells in DMEM (Life Technologies) supplemented with 10% FBS (Life Technologies) and antibiotics (Life Technologies) in 5% CO2 at 37°C in a humidified atmosphere. The cells were used from passage 3 to passage 6.

Animals

Duox1 knockout mice have been previously described [17]. We backcrossed transgenic mice onto C57BJ/6F background for more five generations to obtain wild type (WT) and heterozygous littermate as suitable control. Background C57BL/6F were from Charles River Laboratories (Saint-Germain-Nuelles, France). We housed all mice and cared for them in a pathogen-free facility at Gustave Roussy, and all animal experiments were approved by the Institutional Animal Care and Use Committee at Gustave Roussy.

Genotyping of Duox1 knockout mice

Genotyping primers and protocol are available upon request.

Bleomycine treatment and irradiation procedure

Female 10 to 12 week-old mice (20-25g body weight) were given bleomycin bellon (3.3 units.kg^{-1} in saline, Sanofi-Aventis) or saline alone *via* orotracheal instillation. At designated time points lungs were harvested for further analyses. For irradiation, the mice were irradiated as previously described [18]. For BAL, the trachea was cannulated and washed one times with 0.6 ml sterile PBS at room temperature. Samples were centrifuged at 1,500 rpm for 5 min, and the cell-free supernatants were collected for ELISA assay of TGF-β1 (Legend MAX Free Active TGFβ1, Biolegend) following technical instructions.

H_2O_2 production

H_2O_2 generation was measured in primary lung fibroblasts by the Amplex Red/HRP assay (Molecular Probes, Invitrogen), which detects the accumulation of a fluorescent oxidized product, as previously described [19].

Results (1598 words)

DUOX1 is highly expressed in the lungs of IPF patients and in pulmonary fibrosis mouse models

We first analysed DUOX1 and DUOX2 mRNA expression in both IPF and healthy lung tissues by real-time quantitative RT-PCR (fig 1a) and found an increase in DUOX1 mRNA expression in IPF lung tissues compared with that in control subjects. Notably, this increase, which was associated with an increase in expression of α-SMA, a marker of myofibroblasts, was significant in primary lung fibroblasts from IPF patients (fig. 1b). A clear increase in DUOX1 immunohistochemical staining was observed in both active fibrotic areas and epithelial cells (fig. 1c). Thus, DUOX1 but not DUOX2 is induced in response to lung injury. This finding was confirmed by using the bleomycin model of lung injury (supplementary fig. S1a), in which DUOX1 mRNA expression was also specifically increased in addition to that of its maturation factor DUOXA1, which is essential for the enzymatic activity (fig. 1d). This increase was related to increased mRNA expression of fibrosis markers such as Collagen (Col1a1) and α-smooth muscle actin (ACTA2) as well as that of the pro-fibrotic factor TGF-β (supplementary fig. S1b-S1d). Immunohistochemistry showed that lung fibroblasts highly expressed immunoreactive DUOX1 in fibrotic lungs (fig. 1e). Diphenylene iodonium (DPI), an inhibitor of NADPH oxidases, inhibited bleomycin-induced NADPH-dependent H_2O_2 production (supplementary fig. S1e). Furthermore, we found a specific increase in DUOX1 mRNA in radiation-induced lung fibrosis. (supplementary fig. S2a and S2b)

DUOX1 deficiency decreases bleomycin-induced lung fibrosis

To investigate the biological significance of the inducible expression of DUOX1, we examined the fibrotic response to bleomycin-induced lung injury in DUOX1-deficient mice. Both homozygous (DUOX1-/-) and heterozygous (DUOX1 +/-) mice were used to study the fibrotic response to bleomycin injury. DUOX1-deficient mice were significantly less susceptible to bleomycin-induced lung injury and showed an increase in survival relative to that of WT mice (supplementary fig. 1f). Strikingly, these mice exhibited reduced lung fibrosis, which was correlated with the absence of an increase in H_2O_2 generation (fig.2a). Collagen accumulation was significantly reduced in the lung tissue of DUOX1-deficient mice as determined by real-time QPCR and Sirius red staining (fig. 2b and c). The attenuated fibrosis was further supported by decreased protein levels of fibronectin as analysed by western blot and immunohistochemistry (fig. 2d and e). These results were also observed with the radiation-induced lung fibrosis model (supplementary fig. S2c). These *in vivo* data indicate that DUOX1 is causally involved in driving pulmonary fibrogenesis.

DUOX1-deficient mice display decreased Smad-mediated TGF-β1 signalling in lung tissues

Transforming growth factor (TGF-β1) has been widely recognized as a key fibrogenic cytokine [20]. DUOX1 deficiency leads to a significant increase in TGF-β1 in lung tissues in response to bleomycin treatment as measured by ELISA (fig. 3a). Based on previous results reporting their dysregulation in the lung tissue of IPF patients [21] we analysed the levels of selected cytokines by qRT-PCR (IL-13, IL-6, IL-10 and CXCL15). Regardless of genotype, similar changes were observed (supplementary fig. S3). We next analysed the inflammatory response. Both WT and DUOX1-deficient mice had comparable increases in total inflammatory cell numbers (CD45) in the lungs. Analysis of the influx of neutrophils in BAL showed that, compared with WT mice, DUOX1-/- mice had a significant decrease in the recruitment of neutrophils. Accordingly, the expression of elastase, which is a serine proteinase released from activated neutrophils, was impacted in the same manner (supplementary fig. S4).

To determine the mechanism whereby the absence of DUOX1 results in protection against lung fibrosis, we examined Smad-mediated TGF-β1 signalling in lung tissues. A time-dependent marked increase in Smad3 phosphorylation was observed in lung homogenates from WT bleomycin-treated mice. In contrast, this level only slightly increased 1 week after the treatment in DUOX1-deficient mice and, compared to that of the control, remained low at 3 weeks (fig. 3b). This result was confirmed by immunohistochemistry analysis (fig. 3c). The same results were obtained with the radiation-induced lung fibrosis model (supplementary fig. S5). The bleomycin-induced expression of α-SMA was significantly decreased in lung homogenates from DUOX1-deficient mice (fig. 3d). Taken together these data suggest that DUOX1 may regulate myofibroblast activation by modulating the TGF-β1/Smad signalling pathway.

DUOX1 is regulated by TGF-β1 in fibroblasts

We isolated lung fibroblasts from WT and DUOX1-deficient mice. The extracellular H_2O_2 production measured was related to the genotype, which reflected the level of expression of DUOX1 (fig. 4a). TGF-β1 induced the expressions of both DUOX1 and DUOXA1 mRNA in a dose- and time-dependent manner in WT fibroblasts, in addition to α-SMA and collagen I mRNA expression (fig 4b, supplementary fig. S6), which were otherwise inhibited by DUOX1 deficiency. We next analysed the cell surface expression of DUOX1, as membrane localization is essential to its function. Cell surface biotinylation experiments were carried out with a non-permeable crosslinker on WT fibroblasts. Sulfo-NHS-biotin treatment revealed that DUOX1 was increased on the cell surface after TGF-β1 stimulation (fig. 4c). Collectively, these data show for the first time that TGF-β1 regulates DUOX1 expression in lung fibroblasts. To analyse

the role of DUOX1 in the dynamics of phospho-Smad3 levels we performed a sequential stimulation experiment with increasing doses of TGF-β1. WT and (DUOX1 -/-) lung fibroblasts were first exposed to the indicated doses of TGF-β1 for 48 h and then washed, followed by the addition of fresh medium with TGF-β1 for 1, 2 and 4h. Smad3 phosphorylation kinetics were determined for each treatment schedule (supplementary fig. S7a). Clearly, pre-treatment of the cells for 48 h with increasing doses of TGF-β1 affected the amplitude and the duration of the second TGF-β1-mediated Smad3 signal. This effect was particularly marked in DUOX1-deficient cells (fig. 4d). By contrast, the basal levels of Smad2/3 were not affected. Genotype-based analysis of the time course of TGF-β1-induced phosphorylation of Smad2/3 in primary lung fibroblasts strengthened this result. As expected, the expression of α-SMA was impacted in the same manner (fig. 4e). Once activated by TGF-β1, Smad3 migrates to the nucleus. A strong decrease in the nuclear expression of phospho-Smad3 in DUOX1-deficient fibroblasts was shown by western blot and immunofluorescence analyses (fig. 5a and b). We performed gain-of-function experiments by transiently transfecting DUOX1-/- fibroblasts with pcDNA3.1-HA-DUOX1-expressing vector for 24 h. The cells were treated with or without 5 ng/ml TGF-β1. As shown in Figure 5c, DUOX1 expression promoted TGF-β1-induced Smad3 activation, which was associated with an increase in α-SMA protein. These data suggest a critical role of DUOX1 in a positive feedback mechanism that supports the Smad-dependent pathway in TGF-β1 signalling.

Isolated human lung fibroblasts showed a higher expression of α-SMA in IPF patients when stimulated with TGF-β1 in comparison to that of the control (fig. 6a). DUOX1 mRNA expression was also induced by TGF-β1 (fig 6b). IPF fibroblasts had increased extracellular H_2O_2 production compared to the controls (fig. 6c). Analysis of the time course of TGF-β1-induced Smad3 phosphorylation in control and IPF fibroblasts showed that pre-treatment of the cells with DPI or with catalase, a scavenger of H_2O_2, reduced both the amplitude and the duration of Smad3 phosphorylation (fig 6d).

DUOX1 controls the strength and duration of TGF-β1 signalling

TGF-β1 signalling can be terminated by either dephosphorylation or degradation *via* ubiquitination of phospho-Smad2/3 [22, 23]. To accurately analyse the reduction of Smad2/3 we first treated WT and DUOX1-/- lung fibroblasts with TGF-β1 (2 ng/ml), 30 min) to generate a pool of phospho-Smad2/3 and then with the TGF-β receptor 1 (TBRI) kinase inhibitor SB431542 to prevent rephosphorylation of dephosphorylated Smad2/3 [24] (supplementary fig. S7b). Analysis of the dephosphorylation of Smad2/3 showed that the absence of DUOX1 significantly promoted the reduction in p-Smad2/3 levels (fig. 7a). By contrast, extracellular H_2O_2, generated from glucose oxidase-catalysed glucose oxidation, sustained the level of

expression of phospho-Smad2/3 indicating that this step was H_2O_2 sensitive (supplementary fig. S7c). A more important accumulation of prephosphorylated-Smad3 was observed in IPF-derived fibroblasts compared to healthy fibroblasts and was associated with a slowdown of its reduction (fig. 7b). Importantly, RNAi-mediated knockdown of DUOX1 in IPF-derived cells, which led to a significant decrease in extracellular H_2O_2 production, decreased the TGF-β1-dependent accumulation of phospho-Smad3 (fig. 7c and d). Collectively, these data show that DUOX1-derived H_2O_2 controls the strength and duration of Smad signalling in the TGF-β1 pathway.

DUOX1 inhibits the phospho-Smad3 proteasomal degradation

We next determined how a prolonged treatment with TGF-β1 might affect the steady-state amount of phospho-Smad3. The addition of two cell-permeable, wide-spectrum phosphatase inhibitors (sodium vanadate and okadaic acid) during the 48 h of pre-treatment with TGF-β1 had no effect on the loss of TGF-β1-mediated Smad3 phosphorylation (fig. 8a). In contrast, the addition of the proteasome inhibitor MG132 blocked this effect (fig. 8b). A ubiquitin-dependent degradation of TGF-β1-activated Smads has been previously identified that restricted the amplitude and duration of TGF-β1 gene responses [25]. Since NEDD4L was identified as the principal ubiquitin ligase that selectively targets activated Smad2/3 for destruction we evaluated the effect of its depletion on TGF-β1-induced Smad3 phosphorylation by RNAi-mediated knockdown. The knockdown of NEDD4L prevented the decline in phospho-Smad3 accumulation in DUOX1-deficient fibroblasts, suggesting that the absence of DUOX1 promotes the action of NEDD4L to constrain the signalling capacity of the TGF-β1 pathway (fig. 8c). Neither genotype nor treatment with bleomycin or TGF-β1 impacted NEDD4L protein expression (supplementary fig S8). To further analyse the effect of DUOX1 on phospho-Smad3 stability, we transiently co-transfected DUOX1-/- fibroblasts with vectors encoding DUOX1 and epitope-tagged ubiquitin. The cells were pre-treated with TGF-β1 for 48 h. Immunoprecipitation of ubiquitin followed by immunoblotting with anti-NEDD4L and anti-phospho-Smad3 showed that DUOX1 inhibited the interaction between NEDD4L and phospho-Smad3, thus preventing its ubiquitination and therefore its degradation (fig. 8d). This is modelled in figure 8e.

Discussion (777)

The findings reported here add new insights to our understanding of the regulation of the TGF-β1 pathway and demonstrate a novel role of DUOX1-based NADPH oxidase in regulating the duration of the Smad-dependent TGF-β1 signalling response, which plays a key role in promoting fibrosis [26]. To our knowledge, this study provides, for the first-time, direct experimental evidence that DUOX1 plays a pathological role in pulmonary fibrosis. Our *in vivo* data (IPF patients and bleomycin- and radiation-induced fibrosis in mice) support a role for DUOX1-derived H_2O_2 production in the fibrotic process, particularly in myofibroblast differentiation and activation, whose deregulation has been associated with the progression of the disease.

Until now, DUOX1 expression was believed to be largely restricted to epithelial lineages, including those in the airway [27, 28]. Oxidative stress is an important molecular mechanism underlying fibrosis in the lung [5]. A role for H_2O_2-mediating pulmonary fibrosis was previously supported by the protective effect of catalase, an enzyme that breaks down H_2O_2 [29]. DUOX1 is active on the cell surface, promoting H_2O_2 release into the extracellular space [30-32]. TGF-β1-mediated myofibroblast differentiation was previously shown to be associated with an enzymatic production of extracellular H_2O_2 [33]. Our results reveal that both DUOX1 and its maturation factor DUOXA1 are upregulated by TGF-β1 at the transcriptional level in lung fibroblasts supporting a role of DUOX1-based NADPH oxidase in chronic oxidative stress. The increase of DUOX1-derived H_2O_2 in IPF fibroblasts measured in this study was probably related to an increase of TGF-β expression in the pathologic cells [34].

The extent, duration and potency of signalling, in response to TGF-β1, are intricately regulated by complex biochemical processes [35]. In addition to dephosphorylation by phosphatase [22], ubiquitin-mediated degradation of TGF-β1-activated Smad has been identified as a key mechanism of ensuring the irreversible termination of Smad signalling function [23]. By using TGF-β1 -induced primary lung fibroblast activation as an *in vitro* model, we found that DUOX1 promoted the duration of TGF-β1-activated Smad3 phosphorylation by preventing phospho-Smad3 degradation. NEDD4L has been identified as a principal ubiquitin ligase that selectively targets activated Smad2/3 for destruction [25]. In this study, we showed that DUOX1 negatively regulates the interaction between NEDD4L and phospho-Smad3, thus preventing NEDD4L-mediated ubiquitination of p-Smad3 and therefore its targeting for destruction. The role of extracellular H_2O_2 in this mechanism was supported by the data showing that catalase promoted phospho-Smad3 reduction in IPF fibroblasts while on the contrary, accumulation of H_2O_2 produced by glucose oxidase increased phospho-Smad3 accumulation in DUOX1-deficient fibroblasts. This highlights a role for DUOX1-derived H_2O_2 in positive feedback that amplifies the signalling output of the TGF-β pathway *via* a redox-sensitive mechanism, which may involve cysteine oxidation. The oligomeric state of NEDD4L is essential for polyubiquitin

chain assembly. In addition, this enzyme also has a cysteine in its catalytic site, which is important for its activity [36]. Both the oligomeric state of NEDD4L and its activity may be affected by H_2O_2-mediated oxidation.

H_2O_2 also acts as a chemoattractant for the immune system. In zebrafish, the tissue-scale gradient of H_2O_2 allows leukocyte recruitment to the site of injury, and DUOX knockdown results in decreased immune cell recruitment [15]. As previously observed with allergic airways [37], DUOX1-/- mice had decreased influx of neutrophils in BAL fluid and lung tissue after bleomycin treatment. Interestingly, recruitment of neutrophils to the BAL is an important predictor of early mortality in IPF patients [38]. Thus, DUOX1, in addition to being involved in fibroblast activation, could contribute to regulating the inflammatory response through a neutrophil recruitment to the wound.

Several studies have established a central role of another NADPH oxidase in the pathogenesis of pulmonary fibrosis. TGF-β-induced NOX4 expression was shown to be crucial for mediating ROS production that drives myofibroblast activation in IPF patients and in mice with bleomycin-induced fibrosis [9, 10]. NOX4-derived ROS have been shown to be involved in Smad2/3 phosphorylation induced by TGF-β. However, this induction was inhibited by NAC, an antioxidant, as well as by DPI, suggesting that other NOX-produced ROS are implicated in NOX4 gene expression regulation [10]. This NOX may be DUOX1, which also contributes to TGF-β-mediated upregulation of NOX4 in fibroblasts (data not shown). Thus, DUOX1 appears to be upstream of NOX4.

In normal wound healing, fibroblasts are transiently activated into myofibroblasts to proliferate and deposit the collagen matrix. In contrast, in fibrosis, chronic long-term myofibroblast activation is sustained. TGF-β1 is contextually controlled. This study identified DUOX1 as a potential therapeutic target through its role as a signalling amplifier of the TGF-β pathway, which could contribute to persistent mesenchymal activation and therefore to unrestrained and progressive fibrosis.

Acknowledgements: The authors would like to thank Yann Lécluse (Imaging and Cytometry Platform (PFIC), Olivia Bawa, Mathieu Ayassamy, Laure Touchard, Melanie Polrot and Karine Ser-Le-Roux (Preclinical Evaluation Platform (PFEP)) for their technical assistance and Nicolas Signolle for performing the automated histological image acquisition.

This work was supported by grants from Institut National du Cancer (INCA), Electricité de France (EDF) and Fondation ARC pour la recherche sur le Cancer.

Author contributions: RA Louzada designed and performed experiments, conducted data/statistical analysis and wrote the manuscript; R. Corre performed the experiments and analysed the data; R Ameziane El Hassani initiated experiments; L. Meziani supervised irradiation, BAL and flow cytometry experiments; M Jaillet collected human samples; A. Cazes

analysed IHC data, B Crestani and E. Deutsch reviewed the work; C. Dupuy designed and supervised experiments, provided funding and wrote the manuscript.

References

1. King TE Jr, Pardo A, Selman M. Idiopathic Pulmonary fibrosis. *Lancet*. 2011; 378:1949-61.
2. Fernandez IE, Eickelberg O. New cellular and molecular mechanisms of lung injury and fibrosis in idiopathic pulmonary fibrosis. *Lancet.* 2012; 380:680-8.
3. Selman M, Pardo A. Revealing the pathogenic and aging-related mechanisms of the enigmatic idiopathic pulmonary fibrosis. an integral model. *Am J Respir Crit Care Med*. 2014; 189:1161-72.
4. Kliment CR, Oury TD. Oxidative stress, extracellular matrix targets, and idiopathic pulmonary fibrosis. *Free Radic Biol Med*. 2010; 49:707-17.
5. Cheresh P, Kim SJ, Tulasiram S, Kamp DW. Oxidative stress and pulmonary fibrosis. *Biochim Biophys Acta*. 2013; 1832:1028-40.
6. Rahman I, Skwarska E, Henry M, Davis M, O'Connor CM, FitzGerald MX, Greening A, MacNee W. Systemic and pulmonary oxidative stress in idiopathic pulmonary fibrosis. *Free Radic Biol Med*. 1999; 27:60-8.
7. Daniil ZD, Papageorgiou E, Koutsokera A, Kostikas K, Kiropoulos T, Papaioannou AI, Gourgoulianis KI. Serum levels of oxidative stress as a marker of disease severity in idiopathic pulmonary fibrosis. *Pulm Pharmacol Ther*. 2008; 21:26-31
8. Bedard K, Krause KH The NOX family of ROS-generating NADPH oxidases: physiology and pathophysiology. *Physiol Rev*. 2007; 87:245-313
9. Hecker L, Vittal R, Jones T, Jagirdar R, Luckhardt TR, Horowitz JC, Pennathur S, Martinez FJ, Thannickal VJ. NADPH oxidase-4 mediates myofibroblast activation and fibrogenic responses to lung injury. *Nat Med.* 2009; 15(9):1077-81.
10. Amara N, Goven D, Prost F, Muloway R, Crestani B, Boczkowski J. NOX4/NADPH oxidase expression is increased in pulmonary fibroblasts from patients with idiopathic pulmonary fibrosis and mediates TGFbeta1-induced fibroblast differentiation into myofibroblasts. *Thorax.* 2010; 65(8):733-8.
11. Dupuy C, Ohayon R, Valent A, Noël-Hudson MS, Dème D, Virion A. Purification of a novel flavoprotein involved in the thyroid NADPH oxidase. Cloning of the porcine and human cdnas. *J Biol Chem* 1999; 274: 37265-37269.
12. De Deken X, Wang D, Many MC, Costagliola S, Libert F, Vassart G, Dumont JE, Miot F. Cloning of two human thyroid cDNAs encoding new members of the NADPH oxidase family. *J Biol Chem* 2000; 275: 23227-23233.
13. De Deken X, Corvilain B, Dumont JE, Miot F. Roles of DUOX-Mediated Hydrogen Peroxide in Metabolism, Host Defense, and Signaling. *Antioxid Redox Signal*. 2014; 20:2776-93
14. Edens WA, Sharling L, Cheng G, Shapira R, Kinkade JM, Lee T, Edens HA, Tang X, Sullards C, Flaherty DB, Benian GM, Lambeth JD. Tyrosine cross-linking of extracellular matrix is catalyzed by Duox, a multidomain oxidase/peroxidase with homology to the phagocyte oxidase subunit gp91phox. *J. Cell. Biol*. 2001; 154: 879-891
15. Niethammer P, Grabher C, Look AT, Mitchison TJ. A tissue-scale gradient of hydrogen peroxide mediates rapid wound detection in zebrafish. *Nature* 2009; 459: 996-999
16. Menou A, Flajolet P, Duitman J, Justet A, Moog S, Jaillet M, Tabèze L, Solhonne B, Garnier M, Mal H, Mordant P, Castier Y, Cazes A, Sallenave JM, Mailleux AA, Crestani B. Human airway trypsin-like protease exerts potent, antifibrotic action in pulmonary fibrosis. *FASEB J.* 2018; 32:1250-1264.
17. Donkó A, Ruisanchez E, Orient A, Enyedi B, Kapui R, Péterfi Z, de Deken X, Benyó Z, Geiszt M. Urothelial cells produce hydrogen peroxide through the activation of Duox1. *Free Radic Biol Med*. 2010; 49:2040-8.
18. Meziani L, Mondini M, Petit B, Boissonnas A, Thomas de Montpreville V, Mercier O, Vozenin MC, Deutsch E. CSF1R inhibition prevents radiation pulmonary fibrosis by depletion of interstitial macrophages. *Eur Respir J*. 2018; 51. pii: 1702120.
19. Ameziane-El-Hassani R, Talbot M, de Souza Dos Santos MC, Al Ghuzlan A, Hartl D, Bidart JM, De Deken X, Miot F, Diallo I, de Vathaire F, Schlumberger M, Dupuy C. NADPH oxidase

DUOX1 promotes long-term persistence of oxidative stress after an exposure to irradiation. *Proc Natl Acad Sci U S A*. 2015;112:5051-6.
20. Upagupta C, Shimbori C, Alsilmi R, Kolb M. Matrix abnormalities in pulmonary fibrosis. *Eur Respir Rev*. 2018; 27. pii: 180033.
21. Wynn TA. Integrating mechanisms of pulmonary fibrosis. *J Exp Med*. 2011; 208:1339-50.
22. Bruce DL, Sapkota GP. Phosphatases in SMAD regulation. *FEBS Lett.* 2012; 586(14):1897-905.
23. Iyengar PV. Regulation of Ubiquitin Enzymes in the TGF-β Pathway. *Int J Mol Sci*. 2017;18(4). pii: E877.
24. Inman GJ, Nicolás FJ, Callahan JF, Harling JD, Gaster LM, Reith AD, Laping NJ, Hill CS. SB-431542 is a potent and specific inhibitor of transforming growth factor-beta superfamily type I activin receptor-like kinase (ALK) receptors ALK4, ALK5, and ALK7. *Mol Pharmacol*. 2002; 62: 65-74.
25. Gao S, Alarcón C, Sapkota G, Rahman S, Chen PY, Goerner N, Macias MJ, Erdjument-Bromage H, Tempst P, Massagué J. Ubiquitin ligase Nedd4L targets activated Smad2/3 to limit TGF-beta signaling. *Mol Cell*. 2009; 36:457-68.
26. Zhao J, Shi W, Wang YL, Chen H, Bringas P Jr, Datto MB, Frederick JP, Wang XF, Warburton D. Smad3 deficiency attenuates bleomycin-induced pulmonary fibrosis in mice. *Am J Physiol Lung Cell Mol Physiol*. 2002; 282: L585-93.
27. Fischer H. Mechanisms and function of DUOX in epithelia of the lung. *Antioxid Redox Signal*. 2009; 11:2453-65.
28. Habibovic A, Hristova M, Heppner DE, Danyal K, Ather JL, Janssen-Heininger YM, Irvin CG, Poynter ME, Lundblad LK, Dixon AE, Geiszt M, van der Vliet A. DUOX1 mediates persistent epithelial EGFR activation, mucous cell metaplasia, and airway remodeling during allergic asthma. *JCI Insight.* 2016; 1: e88811.
29. Odajima N, Betsuyaku T, Nagai K, Moriyama C, Wang DH, Takigawa T, Ogino K, Nishimura M. The role of catalase in pulmonary fibrosis. *Respir Res*. 2010; 11:183.
30. Grasberger H, Refetoff S. Identification of the maturation factor for dual oxidase. Evolution of an eukaryotic operon equivalent. *J Biol Chem.* 2006; 281(27):18269-72.
31. Luxen S, Noack D, Frausto M, Davanture S, Torbett BE, Knaus UG. Heterodimerization controls localization of Duox-DuoxA NADPH oxidases in airway cells. *J Cell Sci*. 2009;122(Pt 8):1238-47.
32. Morand S, Ueyama T, Tsujibe S, Saito N, Korzeniowska A, Leto TL. Duox maturation factors form cell surface complexes with Duox affecting the specificity of reactive oxygen species generation. *FASEB J.* 2009; 23(4):1205-18.
33. Waghray M, Cui Z, Horowitz JC, Subramanian IM, Martinez FJ, Toews GB, Thannickal VJ. Hydrogen peroxide is a diffusible paracrine signal for the induction of epithelial cell death by activated myofibroblasts. *FASEB J.* 2005; 19: 854-6.
34. Ramos C, Montano M, Garcia-Alvarez J, Ruiz V, Uhal BD, Selman M, Pardo A. Fibroblasts from idiopathic pulmonary fibrosis and normal lungs differ in growth rate, apoptosis, and tissue inhibitor of metalloproteinases expression. *Am J Respir Cell Mol Biol* 2001; 24: 591-598.
35. Yan X, Xiong X, Chen YG. Feedback regulation of TGF-β signaling. *Acta Biochim Biophys Sin (Shanghai)*. 2018; 50:37-50.
36. Todaro DR, Augustus-Wallace AC, Klein JM, Haas AL. Oligomerization of the HECT ubiquitin ligase NEDD4-2/NEDD4L is essential for polyubiquitin chain assembly. *J Biol Chem*. 2018; 293(47):18192-18206.
37. Chang S, Linderholm A, Franzi L, Kenyon N, Grasberger H, Harper R. Dual oxidase regulates neutrophil recruitment in allergic airways. *Free Radic Biol Med*. 2013; 65:38-46.
38. Kinder BW, Brown KK, Schwarz MI, Ix JH, Kervitsky A, King TE Jr. Baseline BAL neutrophilia predicts early mortality in idiopathic pulmonary fibrosis. *Chest.* 2008; 133(1):226-32.

Figures

Figure 1. DUOX1 is highly expressed in the lungs of IPF patients and in pulmonary fibrosis mouse models. a) Comparative expression of *DUOX1*, *DUOX2* and *ACTA2* genes in human lung tissues (*n=10* per group) and b) in isolated human lung fibroblasts (*n=6* per group) as analysed by qRT-PCR; c) Immunohistochemistry of DUOX1 in lung sections of healthy and IPF patients. Scale bars = 200 µm; Field 1 and Field 2 are magnified from the panel. Fibroblastic foci are shown. d) and e) WT mice were subjected to intratracheal instillation of bleomycin and qRT-PCR for DUOX1, DUOXA1 and DUOX2 was performed; e) Immunohistochemistry of DUOX1 in lung sections of mice at 3 weeks after bleomycin treatment (BLM). Scale bars = 200 µm; Error bars indicate the mean ± SEM. *p<0.05 **p<0.01.

Figure 2. Attenuated pulmonary fibrosis in DUOX1-deficient mice.
DUOX1-/-, DUOX1+/- and their littermates were subjected to an intratracheal instillation of bleomycin. a) Measurement of H_2O_2 production in lung homogenates at the indicated time points after bleomycin treatment (*n=7-8* per group); b) q-RT-PCR analysis of *Col1a1* mRNA expression in lung tissues of mice at the indicated time points (*n=5-8* per group); c) Sirius red staining analysis of lung tissue sections from DUOX1+/+, DUOX1+/- and DUOX1-/- mice at the indicated time points. Scale bars = 500 µm. Quantification of Sirius red staining. The fibrotic area is presented as a percentage (*n=3-6* per group); d) Immunohistochemical analysis of fibronectin in lung sections. Scale bars = 500 µm. Representative images of the staining are shown; e) Western blot analysis of fibronectin in lung tissue. Vinculin was used as a loading control (*n=3-6* per group). Error bars indicate the mean ± SEM. *p<0.05 **p<0.01. ***p<0.001.

Figure 3. DUOX1-deficient mice display decreased Smad phosphorylation in lung tissues. a) ELISA analysis of TGF-β expression in lung tissues at the indicated time points after bleomycin treatment (BLM) (n=4-7 per group); b) Western blot analysis of phospho-Smad2 and phospho-Smad3 in lung tissue at the indicated time points after bleomycin treatment (*n=3-5* per group); c) Immunohistochemical analysis of phospho-Smad3 in lung tissue at the indicated time points. Scale bars = 500 µm; d) Western Blot analysis of α-SMA in lung tissue (*n=5-6* per group). Vinculin was used as a loading control. Error bars indicate the mean ± SEM. *p<0.05

Figure 4. DUOX1 expression is regulated by TGF-β1 and impacts the dynamics of phospho-Smad3 levels in fibroblasts.
a) Measurement of extracellular H_2O_2 production in primary lung fibroblasts isolated from mice with different genotypes (*n=5-7* per group); b) Comparative expression of *DUOX1* and

DUOXA1 genes in wild-type primary mouse lung fibroblasts treated with increasing doses of TGF-β1 (*n=3* per group); c) Western blot analysis of cell surface DUOX1 expression in wild-type primary lung fibroblasts treated for 48 h with TGF-β1 (5 ng/ml). Ponceau Red staining at a corresponding molecular weight area of DUOX1 protein was used as a loading control; d) Western blot analysis of phospho-Smad3 in primary lung fibroblasts isolated from DUOX1+/+ and DUOX1-/- mice after sequential treatment with TGF-β1 as indicated in the figure. Vimentin was used as a loading control; e) Western blot analysis of the time course of TGF-β1-induced phosphorylation of Smad2/3 and expression of α-SMA in primary lung fibroblasts isolated from mice with different genotypes. Vimentin was used as a loading control. Error bars indicate the mean ± SEM. *p<0.05 **p<0.01. ***p<0.001

Figure 5. Transitory expression of DUOX1 in DUOX1-deficient fibroblasts rescues TGF-β1-induced Smad3 activation.

a) Timed induction of phospho-Smad3 in whole-cell lysates and in nuclear fractions from TGF-β1-treated fibroblasts analysed by Western blot; b) Immunofluorescence staining of phospho-Smad3 (nucleus-DAPI); c) DUOX1-deficient fibroblasts were transiently transfected with the HA-DUOX1 expression vector and treated for 24 h with TGF-β1 (2 ng/ml). Whole cell lysates were then collected and phospho-Smad3 and α-SMA expression was analysed by western blot.

Figure 6. DUOX1 is upregulated by TGF-β1 in isolated human lung fibroblasts.

a) Comparative expression of the *ACTA2* gene in healthy and IPF fibroblasts treated with or without TGF-β1 and analysed by qRT-PCR (*n=6* per group); b) TGF-β1 upregulated DUOX1 mRNA expression as analysed by qRT-PCR (*n=6* per group); c) extracellular H_2O_2 production in healthy and advanced patients with IPF (*n=4* per group); d) Effect of pre-treatment (1 h) with 5 μM DPI or with catalase (500 U/ml) on TGF-β1-induced Smad3 phosphorylation as analysed by Western blot. Error bars indicate the mean ± SEM. *p<0.05 ***p<0.001.

Figure 7. DUOX1 deficiency impacts on the dynamics of Smad3 dephosphorylation.

a) Analysis of Smad2/3 dephosphorylation. Wild-type and DUOX1-deficient fibroblasts were treated with 2 ng/ml TGF-β1 for 30 min, followed by washing and the addition or not of TGF-β plus 5 μM SB431542. The graph shows the relative phospho-Smad2/3 levels (over total Smad2/3) with values and error bars representing the mean and standard deviation. (*n=5* per group); b) Experiments equivalent to a) analysing Smad3 dephosphorylation in fibroblasts isolated from healthy and IPF patients (*n=2*, fibroblasts from *two patients*); c) Effect of siDUOX1 vs siControl on extracellular H_2O_2 production activity measured in primary fibroblast isolated from IPF patients (*n=3*); d) Experiments equivalent to a) analysing effect of siDUOX1

vs siControl on phospho-Smad3 dephosphorylation in fibroblasts isolated from IPF patients. Error bars indicate the mean ± SEM. *p<0.05 **p<0.01.

Figure 8. DUOX1 interferes with the destruction of phospho-Smad3 by preventing its interaction with NEDD4L.

a) and b) Western blot analysis of TGF-β1-induced Smad3 phosphorylation in primary mouse lung fibroblasts isolated from DUOX1+/+ and DUOX1-/- mice that were pre-treated with TGF-β1 (5 ng/ml) for 48 h, followed with a pre-treatment for 1 hour with okadaïc acid (100 nM) and orthovanadate (1 mM) or MG132 (20 μM) before stimulation with TGF-β1 (2 ng/ml); c) Effect of siNEDD4L vs siControl on TGF-β1-induced Smad3 phosphorylation in primary mouse lung fibroblasts isolated from DUOX1+/+ and DUOX1-/- mice that were pre-treated with TGF-β1 (5 ng/ml) for 48 h before stimulation with TGF-β1 (2 ng/ml) for 1 h; d) DUOX1-deficient fibroblasts were co-transfected for 48 h with Ub-HA and DUOX1 expression vectors. In control experiments, a GFP-expression vector was used instead of DUOX1. The cells were pre-treated with TGF-β1 (5 ng/ml) before stimulation with TGF-β1 (2 ng/ml) for 2 h. The HA immunoprecipitates and whole cell lysates were immunoblotted with the indicated antibodies; e) Model proposed for the mechanism (see discussion)