ERJ Express. Published on April 20, 2018 as doi: 10.1183/13993003.00122-2018

EUROPEAN RESPIRATORY *journal*

FLAGSHIP SCIENTIFIC JOURNAL OF ERS

Early View

Research letter

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Please cite this article as: Perotin J-M, Coraux C, Lagonotte E, *et al*. Alteration of primary cilia in chronic obstructive pulmonary disease. *Eur Respir J* 2018; in press (https://doi.org/10.1183/13993003.00122-2018).

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Alteration of primary cilia in chronic obstructive pulmonary disease

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Key words: Airway epithelial cells; Chronic Obstructive Respiratory Disease; Cilia; Histopathology

To the Editor,

Chronic obstructive pulmonary disease (COPD) is a major economic and social concern worldwide because of its impact on mortality and morbidity [1]. COPD is characterized by airway epithelium remodelling, a hallmark of dysregulated airway epithelium plasticity [2]. There are currently no available therapeutics to restore the integrity and functionality of the epithelium. Therefore, novel sources of investigation are becoming crucial to understand the alterations at the root of COPD initiation. Non-motile primary cilium (PC) is a solitary sensor organelle playing a critical role in cell cycle control, proliferation, polarity and differentiation, particularly of ciliated cells possessing motile cilia [3-4]. PC are assembled on different types of human cells depending on their state and activities in response to cellular quiescence where they relay extracellular signals and retract upon cell cycle re-entry [5]. Alterations of PC structure and function are responsible for ciliopathies [6-7]. PC may be crucial in determining outcomes during airway epithelial cell differentiation thus we hypothesized that PC are present in adult epithelial cells and may play a key role in airway plasticity. First, we investigated the presence and localization of PC in the bronchial epithelium. Secondly, we analysed the relationships between PC and clinical, functional and histological characteristics of non-COPD and COPD patients.

Patients scheduled for lung resection for cancer (University Hospital of Reims, France) were prospectively recruited following standards approved by the institutional review board (IRB Reims-CHU-20110612). Informed consent was obtained from all the patients. Clinical assessment and pulmonary function tests were performed. Emphysema quantification on the resected lobe was performed visually on thoracic CT-scan by two independent investigators as previously described [8-9]. Formalin-fixed paraffin-embedded (FFPE) lung tissues distant from the tumour were stained with hematoxylin and eosin for bronchial epithelium analysis. Immunofluorescence was performed on FFPE lung tissues with the following primary antibodies: anti-Arl13b (ProteinTech, 1:200); anti-γ-tubulin (Sigma, 1:200); anti-acetylated-α-tubulin (Sigma, 1:1000), anti-GT335 (AdipoGen 1:500), and anti-p63 (R&D systems, 1:100). Images were taken by Confocal Zeiss LSM710 microscope (63xDIC/1.40oil). Primary cilia were analysed on 10 random fields per stained slide. Differences between groups were determined using the Student *t* test or Fisher exact test and associations between variables were analysed using the Spearman rank correlation test. A p-value <0.05 was considered significant.

Thirty-six patients were included, 19 COPD patients (GOLD 1 n=5, GOLD 2 n=12, GOLD 3-4 n=2; aged 66 years [59-73]; FEV_1: 71%[62-81]), and 17 non-COPD patients (aged 69 years [66-76]; FEV_1: 89%[83-102]). CT emphysema score for the resected lobe was significantly higher in COPD group compared to non-COPD group (0[0-0] vs 1[0-2], $p<0.0001$).

Cilia were identified and localized on epithelia with a specific staining for the cilia axoneme and membrane (GTPase Arl13b) and the basal body/centrosome (γ-tubulin) (Figure 1a). Motile cilia were readily identified at the surface of epithelial cells pointing towards the lumen, while solitary cilia (PC) were found on non-differentiated cells of the pseudostratified epithelium as seen during mouse lung development [10]. We confirmed the identification of PC with two additional and well characterized markers of the axoneme (acetylated α-tubulin and GT335) [11] (Figure 1a and data not shown).

Since it has been suggested that PC were absent from adult lung tissues [10] while they are present on other human cells in resting phase [12], we considered to distinguish between histologically "normal" epithelia and "remodelled" epithelia [13]. A normal epithelium was defined as a pseudostratified epithelium (i) presenting the three main cell types (basal, ciliated and goblet cells), (ii) lacking hyperplasia or metaplasia (iii) and showing at least 50% of ciliated cells at the surface.

We analysed bronchial epithelium in non-COPD and COPD groups (Figure 1b). Taking the epithelium as a whole, COPD patients presented a tremendous increase in PC numbers compared to non-COPD patients (68.1[52.2-88.2] vs 9.5[6.1-18.3], $p<0.0001$) (Figure 1c). Interestingly, the normal epithelium of COPD patients showed an increase in PC numbers compared to non-COPD patients (56.5[48.2-67.1] vs 6.2[2.9-19.5], $p<0.0001$) and this increase was more pronounced in remodelled areas (80.7[51.1-109.4] vs 10.7[7.9-14.8], $p<0.0001$). It was particularly striking in basal cell hyperplasia (116.9[91.2-188.2] PC/mm of epithelium in COPD patients vs 15.5[8.9-32.5] in non-COPD patients, $p<0.0001$). Except for one subject, a number of 40 PC/mm in normal epithelia and 50 PC/mm in remodelling epithelia were identified as cut-off between COPD and non-COPD status ($r=0.9215$, $p<0.0001$) (Figure 1d). Interestingly, a significant increase of PC was associated with smoking status ($p=0.01$) but not with smoking history ($p=0.08$), respiratory symptoms including dyspnea score ($p=0.0003$) and chronic bronchitis ($p=0.04$), the severity of airway obstruction (FEV_1: $p=0.002$ and FEV_1/FVC: $p=8.7\ 10^{-7}$) and the presence ($p=0.008$) and the severity of emphysema ($p=0.0009$). Each of these clinical or functional characteristics of patients coupled with the analysis of PC sat apart patients with a COPD as for example the

FEV_1 (%) (Figure 1e, the differences between elevations of linear regressions were extremely significant for each parameter in non-COPD vs COPD groups, $p<0.0001$).

Localization of PC in the lung is consistent with their known functions including acquisition of polarity, migration, differentiation and cell cycle control [14]. PC were rare in epithelia from non-COPD patients suggesting that either PC did not stabilize long enough to be observed or only a few cells were quiescent. The increase of PC among COPD patients may pave the way to a novel understanding of cell plasticity in the context of this disease: (i) if PC are cell cycle progression indicators, are the basal cells no longer able to divide to renew the epithelium? (ii) Is the onset of COPD responsible for the apparition of PC or vice versa? (iii) Can an increase in PC be considered as a marker of abnormal and dysfunctional bronchial epithelium that would be involved in the development of airway obstruction and/or emphysema, especially regarding to airway regeneration anomalies?

Interestingly, PC numbers were altered between a normal and a remodelled area indicating that PC may appear during the renewal or the repair of the epithelium [10]. This is also consistent with the known role of PC in cell migration and tissue homeostasis [15]. Abnormalities of bronchial epithelial wound closure have been shown in severe COPD, and were associated with the severity of airway obstruction and emphysema [8]. Likewise, anomalies of PC could be involved in this phenomenon.

Some limitations must be pointed out in our study. Despite the novelty of the findings, these analyses are exploratory and conducted in a monocentric study including a relatively low number of patients. Thus sample selection and cohort's size represent biases, as well as the lack of "normal controls" which cannot be circumvent in studies conducted from lung resection tissues. Moreover, further investigations are clearly needed to precise the underlying mechanisms of PC alteration.

In conclusion, we have shown an increase of PC on bronchial epithelia associated with clinical, morphological, functional and histological parameters defining COPD. As the presence of PC correlates with clinical features representative of COPD, understanding the dysregulation of PC expression and function would provide additional clues in this complex pathology where the role of the epithelium appears increasingly important. To our knowledge, it is the first observation of non-motile PC in human adult airway epithelia. Whether an accumulation of primary ciliated cells is a disease-driving process or a consequence of epithelium alterations will require further investigations.

FOOTNOTES

Contributors: Study concept: VD; study design: JMP and VD; acquisition data: JMP, EL, GoD, GaD and VD; analysis and data interpretation: JMP, GaD, MP and VD; revision of manuscript: CC, PB, MP and GaD; manuscript writing: JMP and VD

Funding: This work was supported by Région Champagne-Ardenne and the French National Institute of Health and Medical Research (Inserm).

Competing interests: None declared

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FIGURE LEGENDS

Figure 1: Primary cilia are present in adult bronchial epithelia and altered in COPD patients.

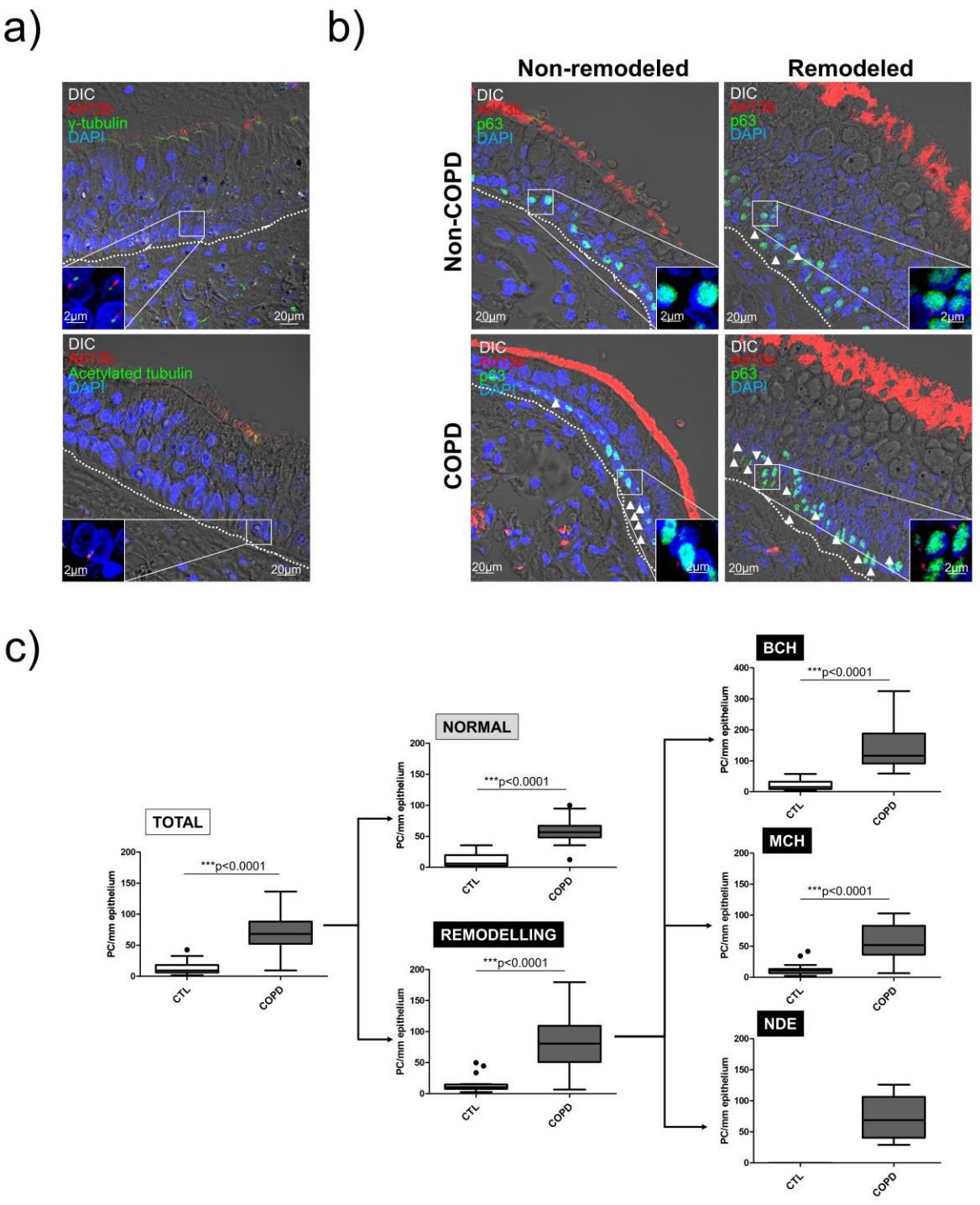
a) Examples of maximum intensity z-stack projection showing the presence of PC on confocal acquisition of the bronchial epithelia for two smoker COPD patients: DIC (grey), Arl13b (red) and γ-tubulin (up, green) or acetylated tubulin (down, green). Dashed lines indicate basal lamina. Boxed areas are shown as magnifications. Nuclei are stained with DAPI (blue).

b) Representative maximum intensity z-stack projections comparing PC on non-remodelled and remodelled areas for non-COPD and COPD patients on confocal acquisition for DIC (grey), Arl13b (red) and p63 (green). Arrowheads show PC localization. Dashed lines indicate basal lamina. Boxed areas are shown as magnifications. Nuclei are stained with DAPI (blue).

c) Box and whiskers plot showing means with IQR of the numbers of primary cilia per epithelium types in non-COPD patients and COPD patients on the epithelium as a whole (total), normal epithelium (normal), remodelled areas (remodelling), basal cell hyperplasia (BCH), mucous cell hyperplasia (MCH) and non-differentiated epithelium (NDE).

d) Graph depicting the repartition of non-COPD (white dots) and COPD (grey dots) patients according to the number of primary cilia per mm of normal (x axis) and remodelled (y axis) epithelium;

e) Graphs depicting the repartition of non-COPD (white dots) and COPD (grey dots) patients according to FEV_1 (%) (x axis) and the number of primary cilia per mm of epithelium (y axis) as a whole (left graph), normal (middle graph) or remodelled (right graph) areas. Lines indicate linear regressions.


a)
b)
Non-remodeled
Remodeled
Non-COPD
COPD
DIC
Ad13b
γ-tubulin
Acetylated tubulin
p63
DAPI
2µm
20µm
c)
TOTAL
NORMAL
REMODELLING
BCH
MCH
NDE
PC/mm epithelium
***p<0.0001
CTL
COPD
d)
PC/mm remodeling
PC/mm normal
r=0,9215
p<0,0001
e)
FEV1 (%)