A novel in vitro tubular model to recapitulate features of distal airways: the bronchioid

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"Take home" message:

A novel tubular engineered lung model called "bronchioid" shows mucociliary function and is compatible with air-liquid interface establishment.

Authors contributions:

- conception and design (PN, GR, ID)
- data acquisition (EM, KR, LA, AL, AES, GR)
- data analysis (EM, KR, AL, AES, ID)
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- resources (PH, TT, MT, MZ, PB)
- drafting the manuscript (EM, KR, ID)
- revision and approval of the final version (All)

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Regarding conflict of interest, ID and PB has 2 patents delivered (EP N°3050574 and EP N°20173595). ID, PH and MZ report grants from the "Fondation Bordeaux Université". MZ reports personal fees from AstraZeneca, Boehringer Ingelheim, CSL Behring, Novartis, Chiesi, GlaxoSmithKline and non-financial support Lilly. PB reports grants and personal fees from Novartis, personal fees and non-financial support from Chiesi, Boehringer Ingelheim, AstraZeneca and Sanofi, personal fees from Menarini and TEVA, outside the submitted work. All other authors declare they have no competing interests.

Abstract

Background: Airflow limitation is the hallmark of obstructive pulmonary diseases. While numerous *in vitro* airway models already exist, chronic obstructives diseases currently lack an 3D culture system enabling to understand how airway remodelling and the associated constrictive limitation develop. Here, the objective was to build a model of small airways, which would overcome the limitations of current culture systems.

Methods: Working with the Cellular Capsule Technology, we developed a so-called bronchioid model, using an innovative tubular cell-based assay and human bronchial adult stem cells derived from clinical samples.

Results: We produced a tubular scaffold made of alginate gel, that drives the spontaneous self-organisation of lung epithelial cells. Fine control of the level of contraction is required to obtain a model of distal bronchiole, with physiologically relevant shape and size. 3D imaging and gene expression analysis of bronchioids made of primary bronchial epithelial cells demonstrates the tubular organization, the formation of epithelial junctions, as well as differentiation into ciliated and goblet cells. Ciliary beating is observed, at a decreased frequency in bronchioids made of cells from COPD patients. The bronchioid can be infected by rhinovirus. An air-liquid interface is introduced, that modulates gene expression.

Conclusion: We provide here a proof of concept of a perfusable bronchioid, with proper mucociliary and contractile functions. Key advantages of our approach, such as the air-liquid interface, the lumen accessibility, the recapitulation of pathological features and possible assessment of clinically pertinent endpoints, will make our pulmonary organoid-like model a powerful tool for pre-clinical studies.

Key words: lung organoid, bioengineering, adult epithelial stem cells, differentiation, COPD, asthma

Abbreviations

ALI	Air-liquid interface
APC	Allophycocyanin
AS	Alginate solution
BEC	Bronchial Epithelial Cell
CCS	Core cell suspension
COPD	Chronic Obstructive Pulmonary Disease
J3B1A	EpH4-J3B1A mammary gland epithelial cell line
EDTA	Ethylene Diamine Tetra-acetic Acid
FEV_1	Forced Expiratory Volume in 1 Second
FITC	Fluorescein Isothiocyanate
FVC	Forced Vital Capacity
HeLa	Cervical cancer Henrietta Lacks cell line
HepG2	Hepatoma G2 cell line
IS	Intermediate D-sorbitol solution
MDCK	Madin-Darby Canine Kidney
MLC	Myosin light chain
MIN6m9	Mouse pancreatic beta cell line
MOI	multiplicity of infection
OWB	Organoid washing buffer
PerCP	Phycoerythrin Peridinin Chlorophyll Protein Complex
PI	Propidium iodure
ROCK	Rho-associated protein kinase
RV16	rhinovirus 16

Introduction

Chronic obstructive diseases such as chronic obstructive pulmonary disease (COPD) and asthma are major public health diseases characterized by airflow limitation. Specific curative treatments are still lacking in these diseases at least because of the paucity of integrative approaches to decipher their pathophysiology, specially that of the distal airways. On the one hand, animal and especially rodent models are widely used for pre-clinical studies, but their airways differ anatomically, histologically and physiologically from those of humans, and they do not fully recapitulate disease hallmarks. So far, they predict poorly which drugs will help treating patients with chronic obstructive diseases. On the other hand, the lung has a complex structure leading to a peculiar stiffness and 3D conformation that is hardly modeled *in vitro*, underlying the need to create adequate complex cellular models.

Various strategies have been proposed to model *in vitro* the conducting bronchi [1]. 2D culture of bronchial epithelial cells at the air-liquid interface (ALI) allows the reconstitution of a fully differentiated epithelium with a functional ciliated function, with an easy access to apical and basal sides [2, 3], but it does not reproduce the three-dimensional architecture essential to model properly the airways. 3D bioprinting is a promising method to build tissue with a relevant geometry [4, 5], especially with the recent development of suitable bioinks, such as those composed of alginate and decellularized tissue, enabling the printing of a tubular structure [6]. However, the length of the tubes obtained is limited, and 3D printing of the last branches of the bronchial tree remains below the resolution limit of current bioprinting techniques. Elegant microfluidic approach has been used to design the so-called « airway-on-a-chip » [7, 8], providing unique advantages such as the ability to perfuse air, particles or nebulize drugs, to incorporate immune cells and the potential application of cyclic stretch to reproduce breathing movements. If the micro-engineered scaffold restrict

morphogenesis to predefined geometry, it does not completely match the exact topology of a bronchi, and does not offer a permissive and remodelable environment.

Others, starting from Benali *et al.*[9] to more recent ones [10–12] have favoured the 3rd dimension with « bronchospheres », in which bronchial epithelial cells, are embedded in a gel and self-organize into spheres with a liquid-filled lumen [13]. These self-renewing organoids exhibite ciliary activity and mucus production. In most of the bronchospheres, the apical side of the cells is facing the inside of the organoid, limiting the access to the lumen, although protocols to reverse airway organoid polarity have been developed [14, 15]. This closed and spherical architecture also impairs the removal of the dead cells inside, and the introduction of an air-liquid interface. Last, formation of invasive tubular from lung organoids have been observed [16], but it remains a stochastic and rather limited process.

The Cellular Capsule Technology, adapted from a co-extrusion microfluidic technique, has been used to encapsulate cells and extracellular matrix proteins in a tubular scaffold made of alginate gel [17]. Cell-laden microfibres have been generated with various cell types, such as endothelial cells, epithelial cells, fibroblasts, skeletal muscle cells and nerve cells [17]. When co-encapsulated, endothelial and vascular smooth muscle cells self-organized into tubular structures modeling vessels [18]. If epithelial cell lines such as the human hepatoma G2 (HepG2) cell line, the mouse pancreatic beta cell (MIN6m9) cell line, the cervical cancer Henrietta Lacks (HeLa) cell line, the Madin-Darby Canine Kidney (MDCK) cell line and the EpH4-J3B1A mammary gland epithelial cell line, have been previously successfully entubulated [17, 19], the behaviour of primary bronchial epithelial cells in this culture system has never been tested.

Here, we aimed at building a tubular organoid-like model of distal airways, built with human primary bronchial epithelial cells. By providing a tubular template made of alginate thanks to the Cellular Capsule Technology, we were able to drive the spontaneous self-organisation of

lung epithelial cells to obtain a 3D “bronchioid” model, with physiologically relevant shape and size. Importantly, the tubular geometry allows lumen access to create an air-liquid interface.

Methods

Patients

Macroscopically normal lung resection material for the purification of basal epithelial cells was obtained from a cohort of patients requiring thoracic lobectomy surgery for nodule or cancer (pN0) (*i.e.*, TUBE, sponsored by the University hospital of Bordeaux, which includes its own local ethic committee (CHUBX 2020/54)). According to the French law and the MR004 regulation, patients received an information form, allowing them to refuse the use of their surgical samples for research. The research was conducted according to the principles of the World Medical Association Declaration of Helsinki. A total of 9 COPD patients with a clinical diagnosis of COPD according to the GOLD guidelines [20] and 15 non-COPD subjects with normal lung function testing (*i.e.*, $FEV_1/FVC > 0.70$) were recruited from the University Hospital of Bordeaux (Table 1). A total of 5 other patients was also recruited from the TUBE cohort for the comparison of bronchioids to classical ALI cultures (Table E1). All clinical data were collected in the Clinical Investigation Center (CIC1401) from the University Hospital of Bordeaux.

Bronchial epithelial cell culture

Human basal bronchial epithelial cells (BECs) were derived from bronchial specimens as described previously [21]. Bronchial epithelial tissue was cultured in PneumaCult™-Ex medium (Stemcell Technologies, Vancouver, Canada) under water-saturated 5% CO_2 atmosphere at 37°C until basal BECs reached 80-90% confluence. For ALI culture, basal BEC were plated (1.10^5 cells per well) on tissue culture treated nucleopore membranes (Ref 3470, 6.5-mm diameter, 0.4-µm pore size, Transwell, Costar) in PneumaCult™-ALI Medium (Stemcell Technologies) applied at the basal side only to establish the ALI. Cells were maintained in culture for 9 or 21 days.

Microfluidic coextrusion device and bronchioid formation

The design of a coextrusion microfluidic device dedicated for bronchioid formation has been previously described for vessels [18]. Using this device with a 450 µm-diameter nozzle, we produced alginate hollow tubes filled with basal BECs. Cells were harvested by using 0.05% trypsin-EDTA (Ethylene Diamine Tetra-acetic Acid, Fisher Scientific) and resuspended in Matrigel (Corning, New York, USA) and Dulbecco's Modified Eagle Medium (Sigma-Aldrich, Saint Quentin-Fallavier, France), both varied from 33.5 to 35% (v/v). Cell loading of the core cell suspension (CCS) varied from 30 to 33% (v/v). Cells were then injected into the central zone isolated from a 2.5% (w/v) alginate solution (AS) (Protanal LF 200 S, FMC corporation, Philadelphia, United States) by a 300 mM intermediate D-sorbitol solution (IS) (Sigma-Aldrich). The experiments were performed using the following injection flow rates: 2 mL/hour (AS), 1 mL/hour (IS), and 1 mL/hour (CCS). With these flow rates, the thickness of alginate walls is approximately 50 µm, resulting in a 350 µm diameter cell tube (Figure 1A). A 100 mM calcium bath at 37°C was used to trigger rapid gelation of the alginate gel while avoiding osmotic shock. Immediately after formation (within less than 10 min), the cell-laden tubes were transferred in Pneumacult™ Airway Organoid Seeding Medium (Stemcell Technologies) at 37°C. After 24 hours, the bronchioids were transferred in Pneumacult™ Airway Organoid Differentiation Medium (Stemcell Technologies) to initiate the differentiation. To inhibit the Rho-associated protein kinase (ROCK), the Airway Organoid Medium was supplemented with Y-27632 (Sigma-Aldrich) at a concentration of 10 µM. Mediums were changed every day.

Western blot

The bronchioids were assayed for myosin light chain (MLC) II and double-phospho-MLC (Thr18, Ser19; PP-MLC) levels by Western blotting. Total protein extracts were obtained by

transferring the bronchioids in Dulbecco's Phosphate Buffered Saline (DPBS, Sigma-Aldrich) for 30 minutes at 37°C with gentle agitation to dissolve alginate. After centrifugation, the pellet was suspended in RIPA Lysis Buffer (Santa Cruz Biotechnology, Dallas, Texas, USA) supplemented with calyculin A (Sigma-Aldrich). These extracts were loaded onto a 4-20 % SDS-PAGE gel (Bio-Rad, Hercules, California, USA), transferred onto nitrocellulose membrane and revealed with a rabbit anti-target antibody (see Table E2). HRP-coupled anti-rabbit secondary antibody was used for revelation using ChemiDoc imaging instrument (Bio-Rad). Protein expressions were normalized using total loading protein (Stain-free system, Bio-Rad).

Quantitative Real-Time PCR

Total RNAs were extracted from bronchioids using RNAeasy kit, according to the manufacturer's instructions (Qiagen, Hilden, Germany). Five hundred nanograms of RNA were reverse-transcribed using the iScript™ Reverse Transcription Supermix (BioRad). cDNA samples were then analysed by qPCR using Perfecta® SYBR® Green SuperMix (Quantabio) through the CFX Connect real-time PCR detection system (Bio-Rad). Primers (*PPIA*, Forward 5′-CGGGTCCTGGCATCTTGT-3′ and Reverse 5′-CAGTCTTGGCAGTGCAGATGA-3′; *RPL13*, Forward 5′-GGGAGCAAGGAAAGGGTCTTA-3′ and Reverse 5′-CACCTGGACAATTCTCCGAGT-3′; *GusB*, Forward 5′-CCATCTGGGTCTGGATCAAAA-3′ and Reverse 5′-TGAAATCGGCAAAATTCCAAAT-3′; *KRT5*, Forward 5′-GCATCACCGTTCCTGGGTAA-3′ and Reverse 5′-GACACACTTGACTGGCGAGA-3′; *TP63*, Forward 5′- CCTCAGGGAGCTGTTATCCG-3′, Reverse 5′-ATACTGGGCATGGCTGTTCC -3′; *SCGB1A1*, Forward 5′-TCCTCCACCATGAAACTCGC-3′ and Reverse 5′- AGGAGGGTTTCGATGACACG-3′;

DNAH5, Forward 5′- AGAGGCCATTCGCAAACGTA-3′ and Reverse 5′-CCCGGAAAATGGGCAAACTG-3′; *AGR2*, Forward 5′-AAGGCAGGTGGGTGAGGAAATC-3′ and Reverse 5′-GTCGAGAGTCCTTTGTGTCCTT-3′; *MUC5AC*, Forward 5′-TACTCCACAGACTGCACCAACTG-3′ and Reverse 5′- CGTGTATTGCTTCCCGTCAA-3′; *EPCAM*, Forward 5′-CCATGTGCTGGTGTGTGAAC-3′ and Reverse 5′-AACGCGTTGTGATCTCCTTCT-3′; *CDH1* Forward 5′-TTACTGCCCCCAGAGGATGA-3′ and Reverse 5′- TGCAACGTCGTTACGAGTCA-3′;) were purchased from Sigma-Aldrich. mRNA expression was determined using the comparative 2-ΔΔCt method and normalized to the mRNA expression level of endogenous reference (*PPIA*, *RPL13* and *GusB*).

Production of rhinovirus 16 (RV16)-GFP

The cDNA pA16-GFP plasmid encoding RV16-GFP, which contains the rhinovirus sequence downstream a T7 promoter, is a kind gift from Yury A Bochkov [22]. The reverse genetics technique developed by Lee et al [23] was used to produce functional RV16-GFP virions. Briefly, for the initial production, the pA16-GFP plasmid was linearized by incubation with the restriction enzyme EcI136II (EcoICRI, Thermo Scientific) at 10 U/µL. After purification using the QIAprep Spin MINI Prep Kit (Qiagen), the DNA was transcribed *in vitro* into RNA by T7 polymerase and then transfected into HeLa cells using lipofectamine (Invitrogen). 24 hours after transfection, the virus produced was purified and titrated by digital PCR after extraction and retrotranscription (Transcriptomic Platform, university of Bordeaux).

Infection with RV16- GFP

An approximately 5 cm-long bronchioid at day 4 to 5 was tranfered into a DMEM-contraining petri dish of 32 mm diameter. The bronchioid was cannulated by a 30G needle

(MicrolanceTM, Becton Dickinson, Franklin Lakes, USA) with a diameter of 300 µm, which is the order of magnitude of the inner diameter of bronchioid. The needle was then connected to a 200 µL-syringe, containing DMEM (Fisher Scientific, Illkirch, France) with RV16-GFP at a concentration of 10 000 particles/µL and supplemented with eosin at 0.1% (Clinisciences, Nanterre, France). The solution was manually injected into the bronchioid lumen, with a visual control thanks to the eosin solution. At 48h post-infection, supernatants were collected and frozen at -80°C for cytokine concentration measurements. The bronchioid was dissociated and the cells manually counted before being processed for FACS analysis. The volume of injection corresponds to the volume of the lumen, which was estimated between 1.1 µL and 1.9 µL, for 5 cm length-bronchioid containing around 15 000 cells, with measured lumen diameters between 170 and 300 µm. This allows to calculate a multiplicity of infection (MOI) between 0.7 and 1.3.

Cytokine production

Bronchioid medium was assayed 48h post-infection for IFN-β and IFN-λ1/3 concentration by ELISA (BioTechne).

Flow cytometry

For ALI culture, epithelial cells in ALI culture were washed in PBS containing 0.5% bovine serum albumin (BSA, Sigma-Aldrich) and 2 mM EDTA (Invitrogen, Fisher Scientific, Illkirch, France) during 4 min at 37°C, and harvested by incubating with 0.5% trypsin- 0.2% EDTA solution (Sigma-Aldrich) during 5 min, with the addition of of Trypsin Neutralizing Solution to neutralize Trypsin (Lonza, Bâle, Suisse), as described in [24]. For bronchioids, alginate dissolution was obtained by incubating the epithelial cell-laden tubes in DPBS during 20 min under gentle agitation. Cells were then mechanically and enzymatically dissociated by

pipetting and by incubating the suspension with 0.5% trypsin- 0.2% EDTA during 5 min. After centrifugation, the cell suspension was filtered through a 70-µm cell strainer (Corning) and immediately subjected to flow cytometry to test for rhinovirus infection. Alternatively, annexin V- Propidium iodide (Fisher Scientific) or DAPI (5µg/ml, Sigma-Aldrich) was used for the detection of apoptotic, dead and living cells, respectively, according to the manufacturer's instructions. Alternatively, cells were stained with anti-EpCAM-Peridinin Chlorophyll Protein Complex (PerCP)-Cy5.5 or its isotype control (see Table E2), and then fixed, permeabilized using the Foxp3 buffer set (Fisher Scientific) or the IntraPrep Permeabilization Reagent Kit (Beckman Coulter). The cell pellet was then stained with anti-pan cytokeratin-FITC, anti-cytokeratin 5-Alexa Fluor 488, anti-acetylated-tubulin-PE, anti-MUC5AC-Alex Fluor 647 or their respective isotype control (see Table E2). FACS data were acquired using a Canto II 4-Blue 2-Violet 2-Red laser configuration (BD Biosciences). Flow cytometry analysis were performed using Diva 8 (BD Biosciences).

Immunostaining

Bronchioids were fixed by using 4% paraformaldehyde (Sigma-Aldrich) diluted in DPBS supplemented with calcium (Sigma-Aldrich) during 30 min at room temperature, and immunostained as described in [25]. Briefly, after fixation, permeabilization and blocking steps were successively performed by incubating the bronchioids with cold DPBS supplemented with calcium containing 0.1% (vol/vol) Tween (P1379, Sigma-Aldrich), and with cold organoid washing buffer (OWB) composed of PBS containing 2g/L of BSA and 0.1% (vol/vol) of Triton X-100 (Biosolve, Dieuze, France), at 4°C during 15 min. The bronchioids were then incubated with primary antibodies diluted in OWB at 4°C overnight, with mild rocking (see Table E2). The bronchioids were washed three times with OWB during two hours each time, and then stained with secondary antibodies, DAPI and phalloidin

diluted in OWB at 4°C overnight, with mild rocking (see Table E2), before three supplementary washes with OWB during two hours each time. Next, the bronchioids were transferred into a µ-slide 4 well chamber slide (Ibidi, Gräfelfing, Germany) and resuspended in a fructose–glycerol clearing solution composed of 60% (vol/vol) glycerol and 2.5 M fructose in dH_2O, or in DPBS supplemented with calcium.

Imaging

Fixed bronchioids were imaged using a confocal Leica SP8 WLL2 microscope on an inverted DMI6000 stand (Leica Microsystems, Mannheim, Germany), using a 20X multi-immersion (NA 0.75 HC Plan Apo CS2) objective. The white light laser 2 (WLL2) was used for excitation of Alexa Fluor 647, 568 and 488 by a range of 650 to 750 nm, 590 to 640 nm and 500 to 550 nm, respectively. The confocal microscope was also equipped with a diode laser at 405 nm. A range of 410-480 nm was used to excite DAPI. The scanning was done using a conventional scanner (400Hz). The image size was 1024x1024 pixels, with a pixel size of 0.568 µm and a voxel depth of 1.040 µm. Detection was achieved with 2 internal photomultiplier tubes (PMT) and 2 internal hybrid detectors. Fluorescence images were acquired with the LAS X software (Leica). Using the Fiji software, the background value was subtracted from the original image and the image contrast in the background-corrected image was adjusted. The images were then processed with the Imaris software (Oxford Instruments, version 9) for segmentation and 3D visualization. The “Clipping Plane” function was used to truncate the image along a given plane in 3D space.

Live imaging to analyse ciliary beating frequency was performed on an inverted Leica DMi8 microscope (Leica Microsystems, Wetzlar, Germany) equipped with a Flash 4.0 sCMOS camera (Hamamatsu, Hamamatsu, Japan). The illumination system used was a Cool LED PE-4000 (CoolLED, Andover, USA). The objective used was a HCX PL Fluotar L 40X dry 0.6

NA PH2. The 37°C/5%CO_2 atmosphere was created with an incubator box and a gaz heating system (Pecon GmbH, Erbach, Germany). Brightfield images were acquired with the MetaMorph software (Molecular Devices, Sunnyvale, USA) for 2 seconds at a frame rate of 1000 images/second, in 9-10 different fields of the bronchioid. The image size was 512 x 32 pixels, with a pixel size of 0.1625 µm. If needed, recursive alignment of the stack of images is performed using the plugin "StackReg" of the Fiji software. Regions of interest were selected on the image generated by a maximum intensity projection using the plugin "Stardist 2D" of the Fiji software. The mean gray intensity was measured in each of these regions over time. Fast Fourier Transformation analysis was applied using Microsoft Excel to retrieve the main frequency (ciliary beat frequency, CBF). In each area, the median CBF is determined from the CBF values in the regions of interest. 9-10 fields are evaluated per donor.

Perfusion

A 3-4 cm-long bronchioid was cannulated by a 30G needle (MicrolanceTM, Becton Dickinson, Franklin Lakes, USA) with a diameter of 300 µm, which is the order of magnitude of the inner diameter of bronchioid. The needle was then connected to a microfluidic system (Fluigent, Le Kremlin-Bicêtre, France) composed of a microfluidic low-pressure generator (FLPG Plus), a microfluidic vacuum pressure-based controller (LineUp™ Push-PullTM), a Non-Invasive Flow Sensor (NIFS) for liquid or air perfusion and a reservoir with a pressurization cap (P-CAP). Air was injected into the lumen at one opened end of the bronchioid, at a continuous flow rate of 0.2 mL/min. Air was released in the medium from the opposite tube end, generating visible air bubbles. Imaging was performed using an Olympus CKX53 microscope with an Olympus DP23 camera with objectives 10X or 20X. Perfusion by air was continued for 4 hours. After stopping the infusion, calcein (Invitrogen) is added to the culture medium at a final concentration of 1 µM and incubated for 15 min at 37°C.

Results

Basal bronchial epithelial cell cultures were obtained from 24 patients (Table 1, n= 15 non-COPD, n=9 COPD). Using the Cellular Capsule Technology, we encapsulated these bronchial epithelial cells in the presence of Matrigel, into tubular structures made of alginate (figure 1a). Of note, cells are injected at a concentration sufficient to allow immediate coverage of the entire alginate walls as soon as the tube is generated. Of the 24 samples, only one culture from non-COPD patient (4%) failed to generate bronchioid, due to a technical problem (figure E1). Seven bronchioids (n=3 non-COPD, n=4 COPD) were fully used before 9 days for early characterization (figure E1). Over the 16 bronchioids kept at least 11 days in culture, 5 (31%) are from patients with COPD. Altogether, it shows that bronchioids are generated with a high success rate, and that they can be kept in culture during several weeks, in a similar way for those derived from COPD and non-COPD patients.

Within the first 24h, epithelial cells formed a monolayer that indeed entirely covered the inner part of the tube (figure 1b). However, as previously shown with epithelial cell lines [19], the bronchioid collapsed 1-2 days after encapsulation (figure 1b). Inhibition of actomyosin contractibility using the Rho-associated protein kinase (ROCK) inhibitor Y-27632 (10 µM) prevented epithelial detachment (figure 1b), while decreasing the level of double-phospho-myosin light chain (Thr18, Ser19; PP-MLC) (figure 1c), suggesting that cell contractility was the main driving force for shrinkage.

Dissolution of the alginate gel was successfully obtained by calcium and magnesion cations depletion during 30 minutes, allowing the obtention of a cell suspension. Analysis of this suspension by flow cytometry demonstrated that the tubular structures remained stable and viable during at least 9 days (Figure 1d). Thus, in the next experiments, the bronchioids were continuously treated with Y-27632 to avoid the collapse. We confirmed the epithelial nature of cells by flow cytometry, showing that at day 1 the cells were almost all positive for EpCAM and cytokeratin, as obtained with differentiated bronchial epithelial cells at the ALI

(Table E1, figure 2a). The mRNA level of *CDH1* (encoding E-cadherin) and EPCAM remained stable over time (figure 2b). Confocal imaging and 3D reconstruction demonstrated the organisation of bronchial cells into a tubular structure with a typical epithelial morphology and a visible lumen, reminiscent of the structure of distal bronchi (figure 2c). The presence of ZO-1 and actin fibers at cell-cell contacts attested the existence of tight junctions (figure 2d). RT-qPCR revealed that the expression of airway basal cell gene keratin 5 (*KRT5)* stayed stable, those of *TP63* progressively declined over time, whereas the club cell secretory marker secretoglobin family 1A member 1 (*SCGB1A1*) was highly upregulated (figure 3a). The expression of ciliated cell markers *FOXJ1* and *DNAH5*, those of the transcription factor anterior gradient 2 (*AGR2*) and the goblet cell marker mucin 5AC (*MUC5AC*) progressively increased in culture (figure 3a). At day 9, the expression of those genes was comparable with bronchial epithelial cells at the ALI for the same time, with the exception of *EPCAM*, *SCGB1A1*, *MUC5AC* whose levels are higher, and *AGR2* whose level is reduced in the ALI condition (figure 2b and 3a). By confocal microscopy, we found at day 11 ciliated cells located at the internal layer lining the bronchioid lumen (figure 3b, movie E1). Most goblet cells were also facing the lumen, with some MUC5AC-positive cells more externally localised (figure 3b). Positive staining for MUC5AC was also found inside the lumen, suggesting mucus secretion. Flow cytometry experiments confirmed the progressive loss of basal cells over time, with a concomitant increase of club, goblet and ciliated cells until day 21 (figure 3c). At day 9, the- cellular composition and viability are very similar in three different portions sampled along the tube (figure E2), indicating a homogenous cellular structure throughout the bronchioid. Altogether, these data are consistent with the induction of distal airway fate in bronchioids, with differentiated cells localized to their corresponding *in vivo* positions.

Using high-speed video microscopy [26], ciliary beating was observed in the bronchioid model (movie E2). For bronchioids generated from 4 different patients, we determined the median ciliary beat frequency (CBF) across different fields of acquisition. Overall, median CBF values ranges ranged from 6Hz to 27Hz, which is in the range of *in vivo* reference CBF [27], and that are also very comparable to those found in bronchial epithelial strips [28], ALI culture [29] and airway organoids [30]. Interestingly, CBF values significant decreased in the bronchoids derived from patients with COPD in comparison to non-COPD patients. This is fully in agreement with the reduced cilia beating frequency shown in nasal cilia samples [31, 32] and airway organoids [30] from COPD patients, demonstrating the potential of the bronchioid model to model respiratory diseases.

We also used the model to test rhinovirus infection, a major trigger of asthma and COPD exacerbation [33, 34]. To track viral infection, we injected through a 30G needle into the lumen of the bronchioid a recombinant rhinovirus type 16 (RV16) accommodating green fluorescent protein (GFP) expression [22] (Figure 5a). Taken in account the calculated volume of the injection, estimated around 1.1 µL and 1.9 µL for a 5 cm length-bronchioid containing around 15 000 cells, the MOI was around 0.7 and 1.3. Forty-eight hours post-infection, around 88% of the cells were GFP-positive (Figure 5b-c), suggesting infection and replication in a vast majority of cells, in agreement with the calculated MOI. Next, we examined effects of RV16 on induction of cytokine secretion. RV16-GFP infection increased the production of IFN-β and IFN-λ, in comparison with the non-infected bronchioid condition (Figure 5d).

To introduce an air-liquid interface, a 30G needle was inserted at day 3 in the lumen of the bronchioid and connected to a dedicated perfusion system (figure 6a). We injected air, as shown by a change of refringence (figure 6a, movie E3), and we maintained perfusion for 4 hours, by adjusting the flow rate to match the circulating flow in distal bronchi with an

internal diameter of 400 μm, *i.e.*, 0.2 mL/min. Calcein staining indicated that cells remained viable after 4h of air perfusion (figure 6b). Air exposure induced a down-regulation of *KRT5* and *MUC5AC* levels, as well as an up-regulation of *SCGB1A1* level (figure 6c), indicating the potential of ALI to affect cell differentiation.

Discussion

Taken together, our bronchioid model offers several key advantages compared with current distal bronchial culture systems, including tubular geometry, lumen access for air and particles exposure, while retaining major characteristics of the airway epithelium. This system is also compatible with multiple biological analyzes such as immunohistochemistry, flow cytometry, transcriptomics and immunoblotting. We expect this model to be instrumental in uncovering cellular mechanisms leading to airflow obstruction and for implementing efficient drug testing assays.

Together with the demonstration of progressive differentiation into ciliated and goblet cells, we provide evidence of ciliary function and mucus production, showing that the bronchioid model very likely displays the fundamental mucociliary clearance property. We also demonstrate that bronchioids derived from cells COPD patients recapitulate important pathological features of COPD, including an impaired mucociliary clearance. At day 21, the cellular composition of the bronchioid is similar to those of airway organoids [10], with a percentage of goblet cells even slightly decreased compared to lung organoids. Thus, the dimension and the geometry of the bronchioid model, closed to a 17th generation bronchiole, as well as its general composition, make it a relevant model of distal airway. However, the cellular composition is not strictly similar to those of distal airways, with in particular the overrepresentation of goblet cells. This is a limitation of the bronchioid model, which can be attributed to the proximal basal cells used in this study [35, 36], and/or to the absence of air exposure. Importantly, our experiments indicated that the introduction of the air-liquid interface (ALI) during 4h induced a down-regulation of *KRT5* and *MUC5AC* levels, as well as an up-regulation of *SCGB1A1* level (figure 6c). These effects are fully consistent with a shift toward a distal phenotype [37], and suggest that the potential of the bronchioid model at the ALI to fully model of distal airways.

While lung organoids have been used to study infection by viruses such as syncytial virus (RSV) [10], enterovirus [38], influenza [11, 39], and acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [30, 40–42], the infection usually requires organoid re-orientation to achieve apical-out polarity [42, 43]. Polarity reversal by suspension culture requires extracellular matrix (ECM) removal, losing the 3D-relevant environment and possibly affecting mecanostransduction pathways. In addition, this step takes at least 1-2 days and does not work at 100%. More importantly, this procedure affects cell viability in differentiated organoid, restricting its use for undifferentiated organoids. In the bronchioid model, we demonstrated efficient rhinoviral infection and replication through intraluminal virus injection. In contrast to microinjection into the center of spherical organoid [44] or organoid mechanical disruption to expose the apical surface [45], our method does not affect the organoid wall, by taking advantage of the easy access to the lumen in the bronchioid model. This procedure is compatible with many types of downstream analyses, including flow cytometry and biochemistry techniques. To our knowledge, we are also the first one to report rhinovirus infection in an organoid-like model, demonstrating the value of bronchioid technology to study infectious diseases and host–pathogen interactions.

Inhibiting the ROCK pathway is considered important for lung organoid generation [46], because of its anti-apoptotic and proliferative effects [47]. We showed here that downregulation of the MLC activity through the ROCK inhibitor Y-27632 was also required to facilitate the generation of an epithelial tubular structure that did not collapse. Importantly, alteration of ROCK activity did not prevent cell-cell adhesion and epithelial differentiation, demonstrating the key role of 3D geometry and subtrate stiffness.

The incorporation of primary bronchial epithelial cells into 3D bioengineered structures is challenging, due in particular to the low attachement capacities of these cells to artificial substrates. Of note, the bronchioid collapse observed in the absence of ROCK inhibition may

also result from insufficient adhesion to the inert alginate walls. Thus, it is likely that there is further room for improvement of bronchioid development, by favouring epithelial cell adhesion to the scaffold [6, 48].

In conclusion, we have generated a new workflow that allows the efficient generation of tubular structures modeling distal airways, built with epithelial cells derived from clinical samples. These bronchioids are susceptible to be perfused with liquid, and more importantly with air to establish an ALI. As meters of tubes are generated per condition and the duration of the assay is relatively short, it also offers the opportunity to apply high throughput methods, in particular for drug screening and testing, in the context of respiratory disease modelling.

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Fig legends

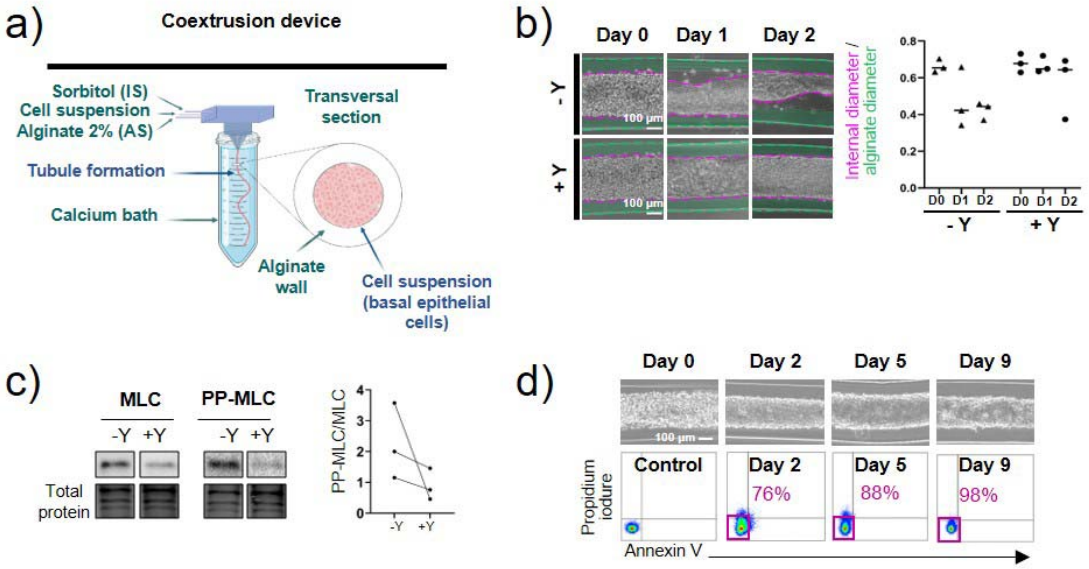

Figure 1. Formation of the alginate tube filled with primary basal epithelial cells, called "bronchioid". a) Schematic of the device to generate bronchioids. The three solutions are injected simultaneously by a computer-controlled pump, inside a 3D printed device soaked in a 100 mM calcium bath. b) Left panel: brightfield images of bronchioids over time, with or without (w/o) 10 µM Y-27632 ("Y"). Green and pink dotted lines indicate the external (alginate tube) and internal (epithelial tube) limits, respectively. Right panel: quantification of external and internal diameters (at least 10 measurements along the same tube for each condition, n=3 experiments). Medians are represented as horizontal lines. c) Immunoblots and analysis of myosin light chain (MLC) II and double-phospho-MLC (Thr18, Ser19; PP-MLC) expressions at day 2 on bronchioids from 3 different donors (i.e. n=3). Total protein stain was loading control. d) Upper panels: brightfield images of bronchioids cultured with 10 µM Y-27632. Lower panels: dot plots showing Propidium iodure (PI) fluorescence (y-axis) versus Annexin V- Allophycocyanin (APC) fluorescence (x-axis) in cells dissociated from bronchioids and analyzed by flow cytometry at indicated time points. Percentages of PI^- $Annexin\ V^-$ cells are shown in pink.

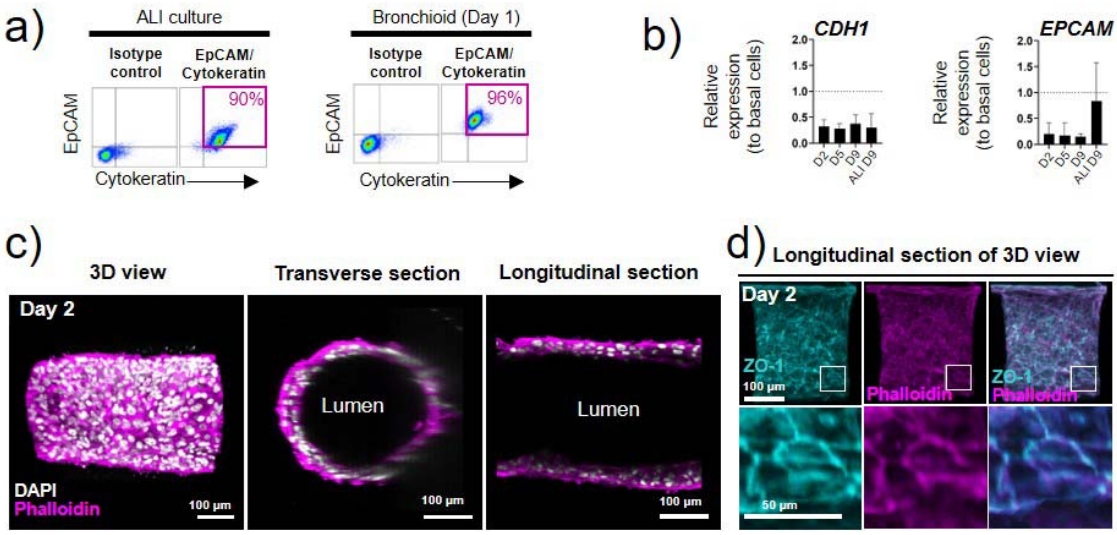

Figure 2. Characterization of the epithelial nature of cells in the the bronchioid model. a) Dot plots represent EpCAM-PerCP-Cy5.5 fluorescence (y-axis) versus pan cytokeratin-FITC fluorescence (x-axis) of cells dissociated from 2D air-liquid interface (ALI) culture and bronchioids at day 1. Gating strategy is shown in the left panels. Percentages of EpCAM^{+} cytokeratin^{+} cells are shown in pink. b) Expression of genes *CDH1* and *EPCAM* in bronchioids over time, and in cells dissociated from 2D culture after 9 days after ALI introduction. The samples are from 6 and 3 different donors for bronchioids and ALI culture, respectively (mean ± standard deviation, n=6 and n=3). Gene expression was normalized to the housekeeping genes *PPIA*, *RPL13* and *GusB* and expressed relative to basal epithelial cells in 2D submerged culture. c-d) Longitudinal, transversal sections and 3D views of 3D reconstructions obtained from Z-stack confocal images of 2-day-old stained for F-actin (phalloidin, magenta) and nucleus (DAPI, white) (c), for F-actin (magenta), ZO-1 (cyan) and nucleus (white) (d).

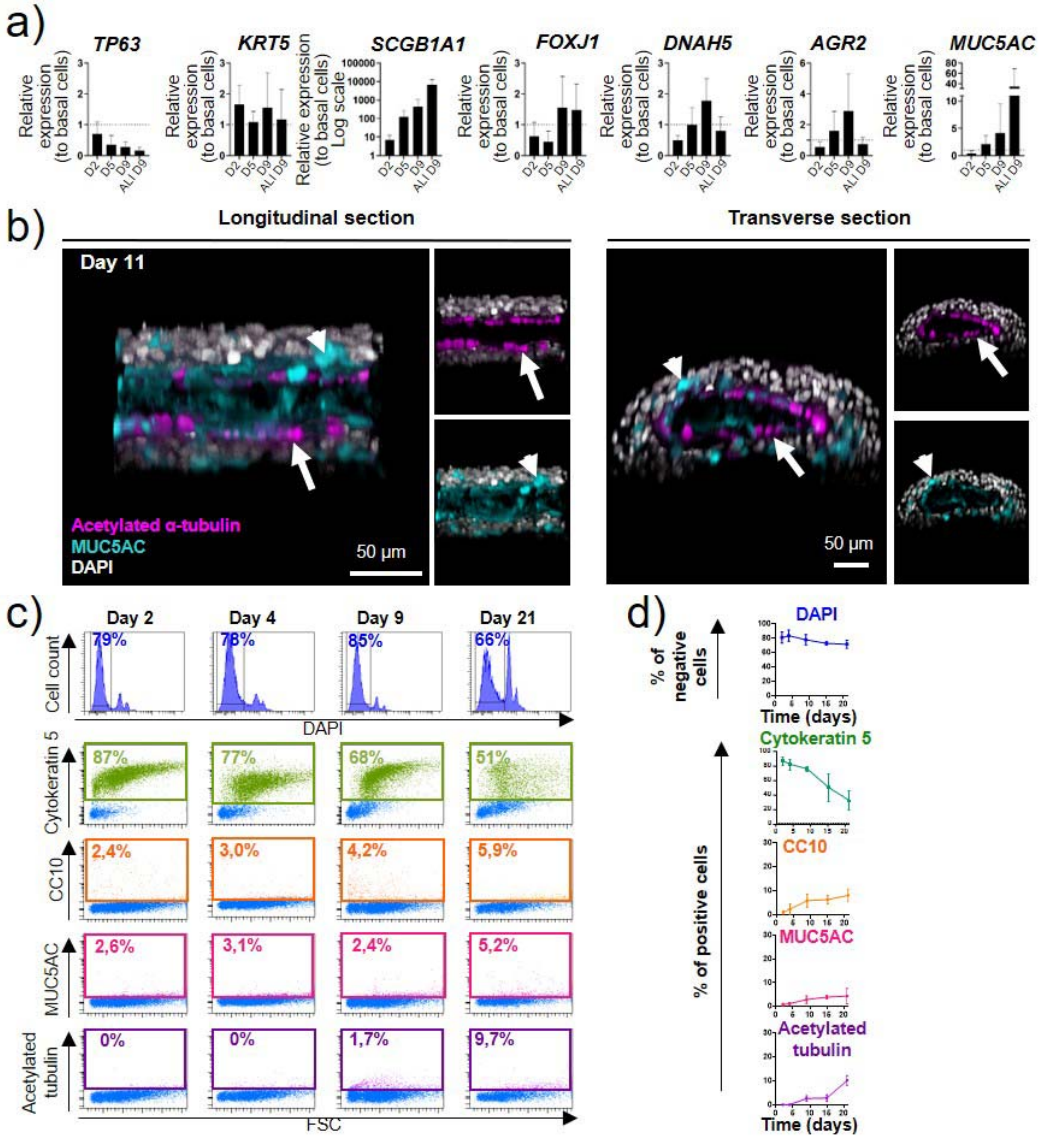

Figure 3. Differentiation induction of primary bronchial epithelial cells into bronchioids. a) Expression of genes *TP63*, *KRT5*, *SCGB1A1*, *FOXJ1*, *DNAH5*, *AGR2* and *MUC5AC* in bronchioids over time, and in cells dissociated from 2D culture after 9 days after ALI introduction. The samples are from 6 and 3 different donors for bronchioids and ALI culture, respectively (mean ± standard deviation, n=6 and n=3). Gene expression was normalized to the housekeeping genes *PPIA*, *RPL13* and *GusB* and expressed relative to basal epithelial cells in 2D submerged culture. b) Longitudinal, transversal sections and 3D views of 3D reconstructions obtained from z-stack confocal images of 11-day-old bronchioid stained for

acetylated α-tubulin (magenta), MUC5AC (cyan) and nucleus (white). Arrows: ciliated cells; arrowheads: goblet cells. c) Histograms represent representative cell count (y-axis) versus DAPI fluorescence (x-axis) of cells dissociated from bronchioids at indicated time points. Dot plots represent representative keratin-5/CC10/MUC5AC/acetylated tubulin fluorescence (y-axis) versus forward side scatted (FSC, x-axis). $DAPI^-$, cytokeratin 5^+ cells, $CC10^+$ cells, $MUC5AC^+$ cells, and acetylated $tubulin^+$ cells are shown respectively in dark blue, green, orange, pink and purple. d) Percentages of $DAPI^-$ cells, cytokeratin 5^+ cells, $CC10^+$ cells, $MUC5AC^+$ cells, and acetylated $tubulin^+$ cells over time. The samples are from 4 different non COPD donors (i.e. n=4).

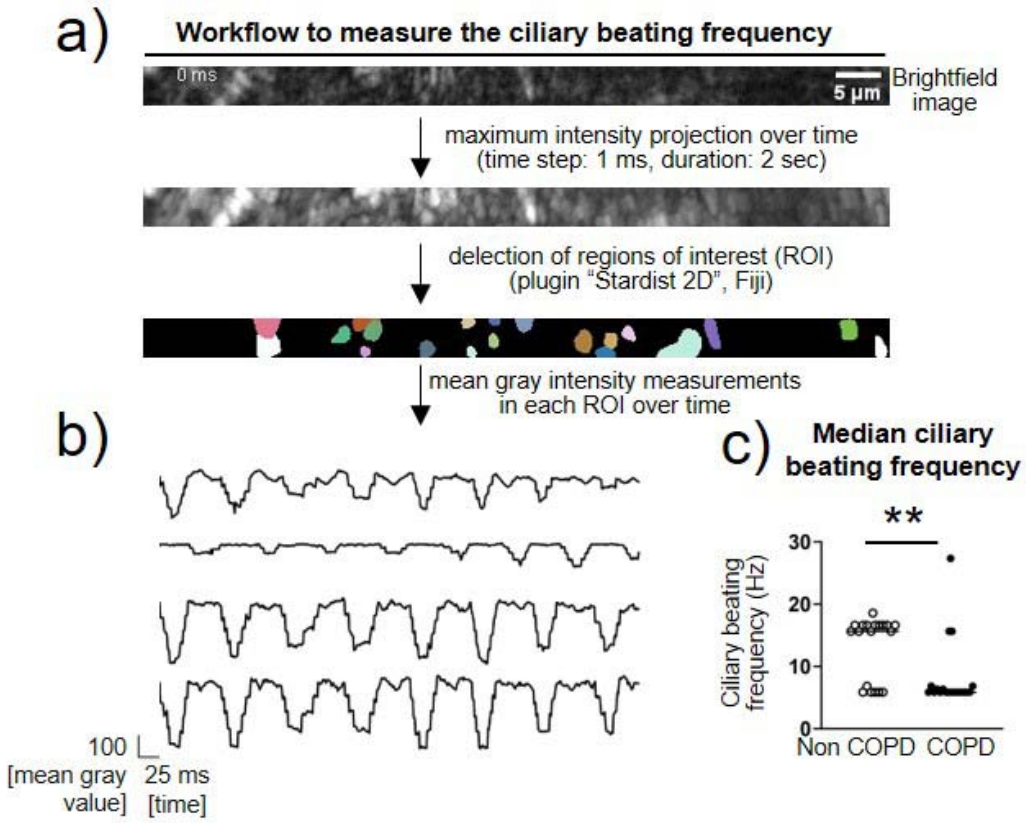

Figure 4. Fast Fourier transform (FFT) analysis of ciliary movement using high-speed video microscopy analysis. a) Schematic workflow to measure the ciliary beat frequency. Representative brightfield image corresponding to a part of a bronchioid at day 20. The coloured areas correspond to the regions of interest determined by the plugin "Stardist 2D" of the Fiji software on the image generated by a maximum intensity projection over time. b) Representative measurements of the mean intensity in regions of interest over time. The main frequency is determined using fast Fourier transform in each region of interest. c) Quantification of ciliary beat frequency (CBF) measurement in Hertz (Hz) of bronchioids derived from 4 different patients (n=2 non-COPD patients, n=2 COPD patients). For each patient, individual values represent median CBF, determined in 9-10 fields. Medians are represented as horizontal lines. **: P <0.01, Mann-Whitney test.

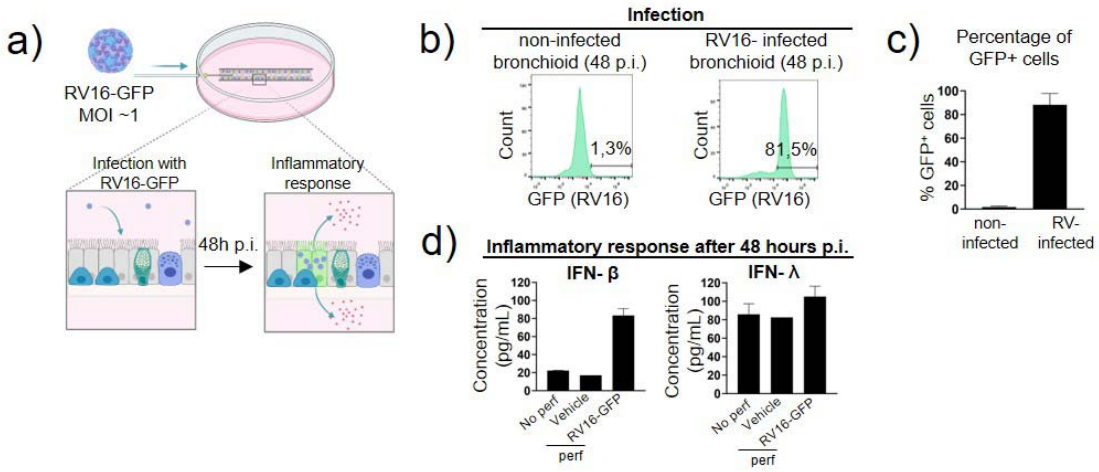

Figure 5. Rhinovirus infection in the bronchioid model. a) Experimental design to test rhinovirus type 16-green fluorescent protein (RV16-GFP) infection. Multiplicity of infection (MOI). b**)** Histograms represent representative cell count (y-axis) versus GFP fluorescence (x-axis) in the different conditions 48h post-infection. The percentages indicate the level GFP positive cells. c) Percentages of GFP^+ cells 48h post-infection, in bronchioids from 2 different donors (i.e. n=2). d) IFN-β and IFN-λ concentrations in the medium from bronchioid cultures in the different conditions.

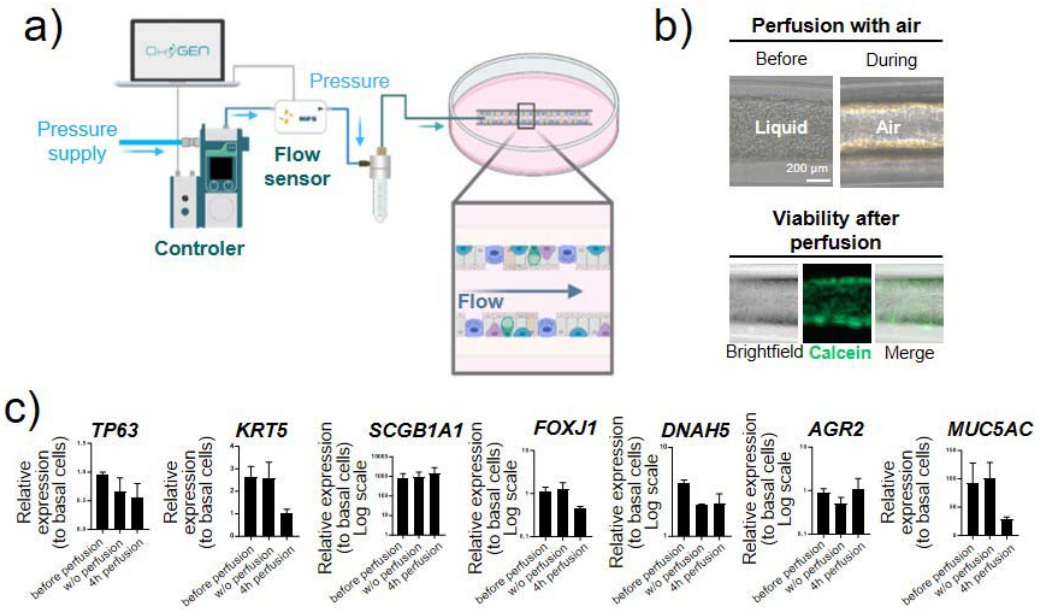

Figure 6. Establishment of an air-liquid interface in the bronchioid model. a) Set up for air perfusion. b) Upper panel: brightfield images of bronchioid before and after air perfusion. Lower panel: brightfield and fluorescence images of bronchioid after 4h perfusion and calcein staining. c) Expression of genes *TP63*, *KRT5*, *SCGB1A1*, *FOXJ1*, *DNAH5*, *AGR2* and *MUC5AC* in bronchioids, without perfusion, and before and after 4h of perfusion, from 2 different donors (mean ± standard deviation, n=2). Gene expression was normalized to the housekeeping genes *PPIA*, *RPL13* and *GusB* and expressed relative to basal epithelial cells in 2D submerged culture.

Supplemental material

Supplemental material includes Tables E1 and E2, figures E1 and E2, movies E1, E2 and E3.

Table 1: Patient characteristics for bronchioid generation

	Non-COPD patients	COPD patients
n	15	9
Age (years)	66.7 ± 8.1	67.5 ± 5.7
Sex (Men/Woman)	8/7	4/5
Current /Former/Non smokers	4/7/4	2/6/0*
Pack years (no.)	35.5 ± 11.1	50.0 ± 34.7*
PFT		
FEV1 (% pred.)	90.6± 30.3	78.2 ± 11.7
FEV1/FVC ratio (%)	76.1± 12.0	67.0 ± 4.6

Plus–minus values are means ± SD. PFT, pulmonary function test; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity.