ORIGINAL ARTICLE

Impaired type I and type III interferon induction and rhinovirus control in human cystic fibrosis airway epithelial cells

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ABSTRACT

Background Rhinoviruses are important triggers of pulmonary exacerbations and possible contributors to long-term respiratory morbidity in cystic fibrosis (CF), but mechanisms leading to rhinovirus-induced CF exacerbations are poorly understood. It is hypothesised that there is a deficient innate immune response of the airway epithelium towards rhinovirus infection in CF.

Methods Early innate immune responses towards rhinoviruses (RV-16, major-type and RV-1B, minor-type) in CF and non-CF bronchial epithelial cell lines and primary nasal and bronchial epithelial cells from patients with CF (n=13) and healthy controls (n=24) were studied.

Results Rhinovirus RNA expression and virus release into supernatants was increased more than tenfold in CF cells compared with controls. CF cells expressed up to 1000 times less interferon (IFN) type I (IFN-α) and type III (λ) mRNA and produced less than half of IFN-β and IFN-λ protein compared with controls. In contrast, interleukin 8 production was not impaired, indicating a selective deficiency in the innate antiviral defence system. Deficient IFN production was paralleled by lower expression of IFN-stimulated genes including myxovirus resistance A, 2′,5′-oligoadenylate synthetase (2′,5′-OAS), viperin and nitric oxide synthase (NOS) 2.

Conclusions This study describes a novel mechanism to explain the increased susceptibility of patients with CF to rhinovirus infections. A profound impairment of the antiviral early innate response in CF airway epithelial cells was identified, suggesting a potential use of IFNs in the treatment of rhinovirus-induced CF exacerbations.

INTRODUCTION

Respiratory virus infections have a significant impact on patients with cystic fibrosis (CF).1–3 They have been linked to increased respiratory symptoms,2 antibiotic use,4 prolonged hospitalisations5 and pulmonary function deterioration in both children and adults with CF.5,6 Up to 40% of pulmonary exacerbations in CF and half of the hospital admissions of infants with CF are associated with respiratory viruses.1,5,6 Rhinoviruses (RVs), the agents of the common cold, have been shown to precipitate the majority of asthma exacerbations7 and nearly half the exacerbations of chronic obstructive pulmonary disease (COPD).8 RVs have consistently been identified as the predominant agents during virus-associated pulmonary exacerbations in CF.9–10

The airway epithelium is central to innate immune responses in the lung, which are crucial in the defence against respiratory viruses.11 Interaction between respiratory viruses and airway epithelial cells (AECs) results in production of antiviral substances including type I (α and β) and III (λ) interferons (IFNs) which contribute to virus clearance.12–15 IFN-β and IFN-λ (IFN-λ1/IL-29, IFN-λ2/IL-28A and IFN-λ3/IL-28B) are the major IFNs produced by bronchial epithelial cells upon virus infection.14 After binding to their specific receptors, they send a signal to the nucleus through the Jak-STAT pathway to induce IFN-stimulated genes (ISGs) leading to the production of several antiviral proteins. These include 2′,5′-oligoadenylate synthetase (2′,5′-OAS), myxovirus resistance (Mx) proteins, viperin and nitric oxide synthase (NOS) 2, which mediate the antiviral actions of IFNs by inhibiting virus replication.11

Recently, deficient induction of type I and III IFNs in bronchial epithelial cells from patients with asthma upon RV infection has been proposed as a mechanism to explain the susceptibility of
these patients towards RVs. We hypothesised that similar deficiencies may be found in CF, and studied the early innate antiviral immune response of CF AECs towards RVs. In this paper we report increased RV replication due to deficient epithelial type I and III IFN production as a novel mechanism to explain the increased susceptibility of patients with CF to RV infections, and thus identify type I and III IFNs as potential treatments for virus-induced exacerbations in CF.

METHODS

Cell and virus culture

Three human bronchial epithelial cell lines with CF and non-CF phenotypes were used: UNCCF2T (F508del/F508del cystic fibrosis transmembrane conductance regulator (CFTR) mutation)/UNCN2T,7 CFBE41o- (F508del/F508del CFTR mutation)/16HBE14o- and IB3-1 (F508del/W1282X CFTR mutation)/IB3-S9.20 Cells were grown as previously described.21 Prior to infection, cells were seeded in 12-well tissue culture plates (Nunc, Rochester, USA) and placed into culture medium without supplements for 24 h. RV16 and RV1B stocks were grown in Ohio HeLa cells (European Collection of Cell Cultures) and stocks prepared as HeLa lysates at 1\times10^7 TCID50/ml.22

Primary human airway epithelial cells

Primary human AECs obtained from patients with CF and healthy subjects were grown in Bronchial Epithelial Growth Medium (Lonza, Switzerland) according to the manufacturer’s recommendations, as described previously.21 At passage 2, cells were seeded onto 12-well plates until 80–90% confluency and grown without supplements for 24 h prior to infection.

Virus infection

Cells were infected with RV16 or RV1B at a multiplicity of infection (MOI) of 2 for 1 h at room temperature with shaking. Virus preparations were removed, cells washed and 1 ml of fresh medium added. As negative controls, cells were treated with medium alone or filtered virus. Plates were incubated at 37°C in 5% CO2. Cell lysates and supernatants were harvested at various time points and stored at -80°C.

RT-qPCR

Quantitative RT-qPCR was carried out using specific primers and probes for RV, IFN-λ1, IFN-λ2/3, IFN-β, interleukin (IL)-8, MxA, 2′,5′-OAS, viperin, NOS2, Toll-like receptor 3 (TLR3), melanoma differentiation-associated gene 5 (MDA5), retinoic acid inducible gene 1 (RIG-1) and 18S (see table E1 in online supplement). Reactions were performed on iCycler (Biorad, USA). Gene expression was normalised to 18S rRNA and expressed as copies per μg of total RNA.

Measurement of virus particle release

Supernatants were serially diluted in Dulbecco’s Modified Eagle Medium containing 4% FCS (Invitrogen, USA) and titrated on HeLa cells to determine the TCID50/ml of RV in the supernatants as described previously.24

ELISA

Protein levels of IL-8, IFN-β and IFN-λ1 (IFN-λ1/IL-29, IFN-λ3/IL-28B) were quantified in supernatants from untreated and infected cell cultures using ELISA kits for human IL-8 (Amersham Biosciences, USA), IFN-β (Biosource International, USA) and IFN-λ1 (R&D Systems, USA).

Biological effect of IFN-β and IFN-λ

Cells were seeded and treated with/without different doses of IFN-β and/or IFN-λ1 before and after infection (Peprotech, USA).

Transfection and RNA interference

Healthy primary nasal AECs were transfected with 100 pmol of scrambled control or three different CFTR siRNAs by using lipofectamin 2000 (Invitrogen, USA) according to the manufacturer’s instructions. siRNA sequences and CFTR sequences of primers/probes are given in the online supplement and in supplemental table E1.

Figure 1 Time course of rhinovirus (RV) replication and release in cystic fibrosis (CF) bronchial epithelial cells. (A) RV16 expression was measured by RT-qPCR after 8 h, 24 h and 48 h of infection (UNCCF2T/UNCN2T cells). Virus replication increased over time and was significantly higher in CF cells (closed circles) than in non-CF cells (open circles) at both 24 h and 48 h. (B) RV16 release into the supernatants of infected cells was determined by calculating the TCID50/ml by titration assay on Ohio HeLa cells. Virus load was significantly increased in CF compared with non-CF cells at both 24 h and 48 h. TCID50, 50% tissue culture infective dose. Data are presented as median (IQR) of 3–6 independent experiments.
**Table 1** Rhinovirus (RV) replication and release in cystic fibrosis (CF) and non-CF bronchial epithelial cells

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<th>Control cells</th>
<th>CF cells</th>
<th>p Value</th>
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<td>RV16 RNA expression (copies/μg RNA)</td>
<td>7.4 (2.1–19.8)×10⁵</td>
<td>88.2 (39.0–6735.0)×10⁵</td>
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<td>RV16 titre (TCID₅₀/ml)</td>
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<td>RV1B RNA expression (copies/μg RNA)</td>
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<td>164.5 (117.8–430.3)×10⁵</td>
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<td>RV1B titre (TCID₅₀/ml)</td>
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<td>RV16 RNA expression (copies/μg RNA)</td>
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<td>RV16 titre (TCID₅₀/ml)</td>
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<td>RV1B RNA expression (copies/μg RNA)</td>
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<td>RV16 RNA expression (copies/μg RNA)</td>
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<td>RV16 titre (TCID₅₀/ml)</td>
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<td>0.001</td>
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<td>RV1B RNA expression (copies/μg RNA)</td>
<td>0.7 (0.2–1.4)×10⁶</td>
<td>61.3 (19.7–83.0)×10⁵</td>
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<td>RV1B titre (TCID₅₀/ml)</td>
<td>3.0 (0.06–0.9)×10⁹</td>
<td>5.5 (0.6–9.0)×10⁹</td>
<td>0.03</td>
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</table>

Data are presented as median (IQR). Cells were infected with RV16 or RV1B. RV RNA expression was analysed by RT-qPCR 24 h after infection. RV particle release was measured in culture supernatants 24 h after infection. TCID₅₀, 50% tissue culture infective dose.

**Statistics**

Data are presented as median (IQR). The Mann–Whitney U test was used to determine differences between groups. Associations were tested by univariable and multivariable regression analyses.

Additional details are provided in the online supplement.

**RESULTS**

**Increased virus replication and release in CF bronchial epithelial cells**

To investigate whether CF cells were more susceptible to RV infection than non-CF cells, we analysed RV RNA expression at 8, 24 and 48 h after infection. We found a more than 1000-fold increase of vRNA expression in CF cells (UNCCN2T) compared with non-CF cells (UNCCF2T) (figure 1A). These results were confirmed by measuring virus particle release into supernatants (figure 1B). Experiments performed in the minor-group RV1B gave similar results (table 1) and replication was lower than for the major-group RV16 as observed by others.¹⁴ ²⁶ The results were replicated in two other CF cell lines (table 1).

**Impaired IFN induction in CF bronchial epithelial cells**

Type 1 (α,β) and III (λ1, λ2/5) IFNs have been described as having strong antiviral properties against RVs.¹⁴ We tested the hypothesis that increased virus replication in CF cells may be attributable to deficient IFN induction. IFN-β, λ1 and λ2/5 gene expression was upregulated after infection in both CF and non-CF but was significantly impaired in CF (figure 2A–C). IFN-α mRNA was poorly expressed and not upregulated.¹⁴ In accordance with mRNA data, IFN-β and IFN-λ protein production was increased in CF and control cells upon RV infection but impaired in CF, both at 24 h and 48 h (figure 2D,E).

**Specific IFN deficiency in CF bronchial epithelial cells**

We assessed whether IFN production deficiency in CF cells was specific and not due to a global downregulation of gene expression and protein production by analysing induction of the proinflammatory cytokine IL-8. IL-8 gene expression was not upregulated after infection in CF or control cells (figure 2F), but similar large amounts of IL-8 protein were secreted at both 24 h and 48 h after infection in CF and non-CF cells (figure 2G).

**Deficient induction of IFN-stimulated genes in CF bronchial epithelial cells**

To study the downstream effects of impaired IFN induction in CF, we investigated the expression of MxA, 2'5'-OAS, viperin and NOS2. Expression of all ISGs was induced in CF and non-CF cells upon infection, but CF cells expressed up to 1000 times less ISG mRNA (figure 3A). ISG expression was inversely related to RV replication (2'5'-OAS: R²=0.39, p=0.042) and positively to IFN-β production (2'5'-OAS: R²=0.40, p=0.002; viperin: R²=0.16, p=0.106; NOS2: R²=0.39, p=0.021) (data for MxA shown in figure 3B,C). A similar positive relationship was found between ISG expression and IFN-λ production (not shown). Associations remained significant after adjusting for disease group in multivariable regression analysis.

**Exogenous IFN restores virus control and decreases virus-induced cytotoxicity in bronchial epithelial CF cells**

Having demonstrated increased virus replication and a selective IFN production deficiency in CF after RV infection, we tested the ability of exogenous IFN-β/IFN-λ to restore antiviral pathways. Both exogenous IFN-β and IFN-λ (100 pg/ml) increased levels of ISGs (figure 4A) and decreased RV16 RNA expression and release into supernatants of CF cells (figure 4B,C) to the level of control cells. IFN-β had a more pronounced effect than IFN-λ. No additional effect was observed when CF cells were treated with IFN-β and IFN-λ together. There was no effect of IFN treatment in control cells. Additionally, previously reported increased cytotoxicity upon RV infection in CF cells could be decreased to the level of control cells after exogenous IFN treatment (see figure E1 in online supplement).

**Impaired virus control and IFN induction in primary CF airway epithelial cells**

To assess whether our findings in cell lines could be replicated in primary AECs, we investigated virus replication in nasal and
We found impaired control of RV replication in CF, with the virus load being 100-fold higher in nasal CF AECs and tenfold higher in bronchial CF AECs than in non-CF cells (figure 5A,B). IFN-β mRNA expression was 100 times lower in nasal CF AECs and 10 times lower in bronchial CF AECs compared with controls (figure 5C,D). Similar findings were obtained for IFN-β protein both at 24 h and 48 h (figure 5E,F). There was no association between virus load or IFN production and clinical markers in patients with CF (age, forced expiratory volume in 1 s, Pseudomonas aeruginosa colonisation). However, there was an inverse relationship between IFN-β levels and RV replication in nasal AECs (R²=0.59, p<0.001) and bronchial AECs (R²=0.29, p=0.03; figure 6) which remained significant after adjusting for disease group in multivariable regression analysis.

As pattern recognition receptors (PRRs) including TLR3, MDA5 and RIG-I play a central role in RV recognition and virus-induced IFN responses, we investigated whether expression of these receptors differed in CF compared with non-CF. Basal expression of all receptors was similar in CF and non-CF (figure E2 in online supplement).

**Increase in virus replication and impaired IFN responses are not directly linked to CFTR dysfunction**

We examined RV replication and IFN responses after CFTR inhibition in healthy primary AECs. Upon transfection of siRNA targeting CFTR, levels of CFTR mRNA were decreased up to 80% in control and RV16-infected cells (figure 7A). However, there were no differences in virus replication or in IFN mRNA levels between control and CFTR siRNA-transfected cells (figure 7B,C).

**DISCUSSION**

Strategies aimed at controlling respiratory virus infections may limit exacerbations and deterioration of pulmonary function in patients with CF. Approaches targeting respiratory viruses in CF have included yearly immunisations, the use of neuraminidase inhibitors or adamantanes against influenza and prophylactic administration of immunoglobulins against respiratory syncytial virus. However, no treatment against rhinoviruses is currently available. Impaired ISG production linked to impaired antiviral responses may partially explain the previous observations with STAT1/NOS2 and underscore the potential therapeutic benefit of IFN therapy for RV infections in patients with CF.

We first identified differences in innate antiviral responses between CF and non-CF cells using three different well-characterised cell lines. Our data show that all cell lines have a similar phenotype with regard to impaired antiviral responses. We conclude that this is not an artefact of cell line immortalisation or transformation specific to a particular cell line. These results were confirmed in primary AECs from patients with CF and healthy controls. This is the first time impaired innate antiviral immunity has been identified in both nasal and bronchial AECs obtained from patients with CF and healthy subjects at a median (IQR) age of 15.1 (9.6–26.7) years (table 2).
bronchial cells in CF. This is important, as many respiratory virus infections may start as upper airway infections and proceed to the lower airway. Experimental RV infections are often given in the nose and proceed to the lung causing lower airway inflammation, symptoms and reduction in lung function.36–38 Our data support a hypothesis that impaired antiviral immunity in the nose may lead to greater virus dissemination and hence greater risk of lower airway infection.

To understand mechanisms behind the increased susceptibility of the CF airway epithelium towards RVs, we investigated epithelial IFN responses. We observed significant IFN-β, IFN-λ1 and IFN-λ2/3 production after infection in both CF and non-CF, which is consistent with data from the literature reporting that IFN-β and IFN-λ but not IFN-γ or IFN-α are produced by the airway epithelium in response to viruses.14 IFN induction was profoundly impaired in CF cells at the mRNA expression and protein level. Impaired IFN production was a selective defect, as the proinflammatory cytokine response in CF ACEs was similar in CF and non-CF. The relevance of this defective IFN production was demonstrated by the inverse relationship between IFN production and virus replication: whereas primary AECs obtained from patients with CF produced low levels of IFN and were unable to control virus replication, healthy AECs produced high levels of IFN associated with low virus replication. The addition of exogenous IFN to CF cells restored control of virus replication, proving that IFN deficiency is the cause of impaired virus control in CF. Zheng et al32,33 previously reported increased parainfluenza replication in CF AECs from lung explants. They identified defective IFN signalling with impaired induction of NOS2 and 2′,5′-OAS as possible mechanisms, but did not study IFN-β, and the IFN-λ family was only very recently described at the time. Our findings of impaired IFN induction associated with deficient induction of ISGs including NOS2 and 2′,5′-OAS suggest that their results32,33 were a consequence of defective IFN induction, although we cannot rule out the possibility that other mechanisms independently contribute to impaired antiviral control of the CF airway epithelium. Others have reported similar IFN responses upon RV infection in well-differentiated AECs from patients with CF and healthy controls.39 Technical issues such as virus strains used, infection intensity and cell culture conditions might account for these apparently dissimilar results. Although we did not formally rule out increased virus binding or endocytosis in CF cells, our findings of similar viral loads at early time points in CF and non-CF cells and of defective IFN induction argue against this mechanism as a cause of increased susceptibility of the CF airway epithelium towards RVs. In addition, similar expression of RV receptors

Figure 3  Deficient induction of interferon-stimulated genes in CF bronchial epithelial cells after RV infection. (A) CF (UNCCF2T) and control (UNCN2T) bronchial epithelial cells were infected with RV16 or treated with medium alone [M]. Myxovirus resistance A (MxA), 2′,5′-oligoadenylate synthetase (OAS), viperin and nitric oxide synthase (NOS)-2 gene expression levels were measured by RT-qPCR at 8h post-infection. Expression of all ISGs increased in both CF and control cells compared to medium control ([M]) (***p < 0.001), but was significantly impaired in CF compared to control cells. Data are presented as median (IQR) of 3–4 independent experiments. (B) MxA gene expression was inversely related to virus replication. Linear regression R2 was 0.67, **p = 0.001. (C) MxA gene expression was positively related to levels of IFN-β protein in supernatant. Linear regression R2 was 0.73, p < 0.001. Associations remained significant after adjusting for disease group in multivariable regression analysis. White dots: control cells; black dots: CF cells.
Our findings may have direct therapeutic relevance as we corrected impaired virus control and defective ISG induction by adding exogenous IFN. IFN-β had the most pronounced effect, suggesting it as the preferred candidate. Addition of IFN-β restored levels of ISGs to control levels, which was not achieved by the addition of IFN-α or a cytokine cocktail in the study by Zheng et al. So far, there has been only one therapeutic trial using IFN

**Table 2** Characteristics of patients with cystic fibrosis (CF) and healthy control subjects

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*Atopy defined as a positive history of hay fever, eczema or asthma.†Steroid use defined as any treatment with systemic, inhaled or nasal steroids within the past 3 months.‡Pseudomonas aeruginosa (PA) colonisation defined as one or more PA-positive oropharyngeal cultures during the preceding 12 months; negative: no growth of PA in previous 12 months.

FEV₁, forced expiratory volume in 1 s as percentage predicted; ND, not done.
application in patients with CF. Moss et al. tested the effect of aerosolised IFN-γ1b in patients with CF with mild to moderate lung disease but did not find any beneficial effect. The lack of efficacy of this approach may be due to the fact that IFN-γ1b is a type II IFN which is mainly produced by natural killer cells and T lymphocytes and not by the bronchial epithelium. Topical type I IFNs have successfully been used in the treatment of severe asthma, leading to improved lung function and reduced need for oral corticosteroids. A similar approach may benefit patients with CF.

We were able to gain an insight into the mechanisms leading to deficient IFN induction in the CF airway epithelium. We and others have recently demonstrated a lack of exaggerated inflammatory responses and increased AEC necrosis upon RV infection in CF. Here we show that impaired IFN induction is not a consequence of virus-induced increased cell death as exogenous IFN decreased cytotoxicity in CF cells to the level of control cells, but rather that impaired IFN induction results in enhanced cell death. Further, we found that deficient IFN production was not due to altered virus recognition by CF ACEs as expression of dsRNA PRRs was similar in CF and control cells. The data suggest that aberrant PRR signalling leads to deficient IFN production in CF. Indeed, Chattoraj et al. recently demonstrated inhibited RV-stimulated Akt phosphorylation and decreased interferon regulatory factor-3 phosphorylation in CF but not in normal AECs after Pseudomonas aeruginosa infection. Susceptibility to RV infection associated with deficient IFN production is not unique to CF and has been shown in asthma and COPD. Because CF, asthma and COPD are all chronic inflammatory airway diseases, we speculate that...
deficient antiviral responses are the consequence of a chronic proinflammatory state rather than directly linked to disease-specific characteristics such as CFTR dysfunction. Indeed, in our study, CFTR inhibition in healthy AECs did not lead to impaired IFN responses and higher virus replication. Recent evidence suggests that a chronic inflammatory milieu, such as that seen in the context of bacterial infection or atopy, suppresses IFN responses towards virus infections in the airways.39 46 However, it might be that, in CF, both inflammatory milieu and loss of CFTR function lead to defective epithelial IFN production upon virus infection through, for example, increased and persistent oxidative stress.39

Our study has some limitations. We have used primary and immortalised ACEs grown as monolayers, and full differentiation of cells with addition of factors of the naturally occurring microenvironment may have been needed to better mimic virus effects on ACEs. Furthermore, the number of study subjects was relatively small, which did not allow us to examine the effects of genetic and environmental factors. Finally, we did not explore synergisms between viruses and bacteria which might be of relevance to antiviral responses of the CF airway epithelium.39

In conclusion, our findings demonstrate a deficient antiviral response to RV infection in CF AECs. Impaired induction of IFN-β, IFN-λ and ISGs results in increased virus replication. This defect can be restored in vitro by the addition of exogenous IFN which limits virus replication to levels observed in normal cells. We therefore suggest that IFNs, particularly IFN-β, might provide novel therapeutic avenues for the treatment of virus-induced CF exacerbations for which very few therapeutic options currently exist.

Acknowledgements The authors thank all study participants and their families for participating in the study; Kathrin Mühlemann and Susanne Aebi from the Department of Infectious Diseases, University of Bern, Amiq Gazdar, Patrizia Castiglioni and Fabian Blank from the Division of Respiratory Medicine, University of
REFERENCES


Impaired type I and type III interferon induction and rhinovirus control in human cystic fibrosis airway epithelial cells

Marjolaine Vareille, Elisabeth Kieninger, Marco P Alves, Brigitte S Kopf, Alexander Möller, Thomas Geiser, Sebastian L Johnston, Michael R Edwards and Nicolas Regamey

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Notes
Retraction

Marjolaine Vareille,1,2,3,4* Elisabeth Kieninger,1,4* Marco P. Alves,1,4 Brigitte S. Kopf,1,4 Alexander Möller,5 Thomas Geiser,6 Sebastian L. Johnston,7 Michael R. Edwards,7 and Nicolas Regamey1,4

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In our article recently published in Thorax, we described a novel mechanism explaining the increased susceptibility of patients with cystic fibrosis (CF) to rhinovirus infections, namely defective interferon type I and III production by CF airway epithelial cells. In experiments performed after publication of the article we were unable to consistently replicate our findings of deficient interferon type I and III production by CF airway epithelial cells upon rhinovirus infection. In the light of these results, we carried out detailed investigations of the data reported in the above manuscript and regretfully found evidence of deliberate manipulation of experimental data by the first author Dr M. Vareille. This manipulation was accompanied in some instances by absence of original data files. The manipulation/original data absence involved data presented in most, if not all of the figures, thus we wish to fully retract the paper and apologise to the readers of Thorax and to the scientific community for the inconvenience this has caused.

We also checked data published by our group in manuscripts on which Dr Vareille was a co-author and found that data published in these manuscripts had not been manipulated. These two manuscripts, whose data and conclusions we stand by are:


and


Dr. Vareille has received a letter from the Secretary General of the University of Bern condemning her scientific misconduct as a severe offence against the rules of scientific integrity. Her current employers have also been informed.

All co-authors of the publication including Dr. Vareille concur with the retraction statement.