Acute effects of viral respiratory tract infections on sputum bacterial density during CF pulmonary exacerbations

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Abstract

Background: Airway proliferation of Pseudomonas aeruginosa bacteria is thought to trigger CF exacerbations and may be affected by the presence of viral infections.

Methods: A 2-year prospective study was conducted on 35 adults with CF. P. aeruginosa sputum density was analyzed during stable, exacerbation and post exacerbation assessments. Upon exacerbation, samples were sent for PCR detection of respiratory viruses and the sputum density of P. aeruginosa in patients with a viral infection versus those without was compared.

Results: Twenty-two patients experienced 30 exacerbations during the study period; 50% were associated with a viral infection. There was no change in sputum density of P. aeruginosa from the stable to exacerbation state when measured by quantitative culture or by PCR. Virus-associated exacerbations did not result in significant increases in P. aeruginosa sputum density compared to non-viral exacerbations.

Conclusion: Sputum density of P. aeruginosa was not increased at the time of CF exacerbation and was not influenced by the presence of viral infection.

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Keywords: Cystic Fibrosis; Pseudomonas aeruginosa; Viral infection; CF exacerbation

1. Introduction

Lung disease in cystic fibrosis (CF) is characterized by chronic bacterial airway infection punctuated by acute deteriorations termed pulmonary exacerbations. Pulmonary exacerbations are defined clinically by a combination of signs and symptoms such as increased cough, sputum purulence, dyspnea, and weight loss [1]. CF exacerbations have been associated with declining lung function, have a negative impact on quality of life, and are associated with significant cost [2–4]. In addition, frequent exacerbations are associated with an increased risk of death and lung transplant [3].

The pathophysiology of exacerbations remains unclear. They have been linked with clonal expansion of existing bacteria rather than acquisition of new bacteria [5], and it has been hypothesized that exacerbations might be caused by increased airway bacteria proliferation and changes in bacterial phenotype [1,6]. Some studies have found that sputum bacterial density decreases following exacerbations as patients improve clinically...
with antibiotics [7–12]. These findings lead to the hypothesis that an increase in bacterial density immediately before, or at the time of exacerbation, might contribute to the pathophysiology of exacerbation. However, prospective studies investigating this hypothesis are relatively lacking.

Viral infections are thought to be triggers of CF exacerbations, though their prevalence in studies varies from 5 to 68% [13–16]. Exacerbations caused by viral infections have been associated with longer courses of antibiotics and worsening lung function [15,17]. In addition, patients with virus-associated exacerbations have been reported to have more severe clinical presentations and a shorter duration to the next exacerbation than those with non-virus associated exacerbations [15].

The evidence suggesting that viral infections are associated with changes in bacterial density in the lungs is relatively scanty. In a study of 17 adult patients with CF and chronic bacterial infection, viral infections were associated with a small increase in sputum bacterial density at the time of CF exacerbation [13]. An association between viral infection and bacterial burden has also been shown in other respiratory illness such as chronic pulmonary obstructive disease (COPD). Experimental rhinovirus infection in patients with COPD resulted in an increase in sputum bacterial density, which peaked 15 days post-rhinovirus infection [18,19]. These results suggest that viral infection may be instrumental in precipitating secondary bacterial infections.

The objective of this study was to determine if there was a change in the sputum density of Pseudomonas aeruginosa at the time of pulmonary exacerbation compared to the stable state. In addition, we wanted to determine whether changes in bacterial sputum density were affected by the presence of acute viral respiratory tract infections.

2. Methods

2.1. Study design and participants

This was a two-year prospective observational study of adult CF patients who were evaluated during stable, exacerbation, and post-exacerbation states. Subjects were recruited from the CF clinic at The Ottawa Hospital starting in June 2012 and were followed until April 2014. Adult patients (>18 year) with confirmed CF who were able to spontaneously produce sputum and had a history of chronic infection with P. aeruginosa (at least 2 positive sputum cultures for P. aeruginosa in the 12 month period before study entry) were recruited. Ethics approval for this study was obtained from the Ottawa Hospital Research Ethics Board in accordance with the amended Declaration of Helsinki and informed written consent was obtained from all subjects.

Patients were enrolled in the study when stable and were reassessed every 3 months. At each visit, patients provided a sputum sample for quantitative bacterial density assessment and RT-qPCR (reverse transcription real-time polymerase chain reaction) for virus detection. During episodes of worsening respiratory symptoms, patients were instructed to contact the CF staff. The patients were assessed to determine if they met criteria for a pulmonary exacerbation defined by criteria published by the 1994 Cystic Fibrosis Foundation Microbiology and Infectious Disease Consensus Conference [20].

After confirmation of a CF exacerbation, the patient was asked to provide a spontaneous sputum sample, and a nasopharyngeal (NP) swab was taken for respiratory virus assessment. Patients were then treated with antibiotics if necessary and asked to return a minimum of 30 days later for a post-exacerbation assessment.

2.2. Quantitative bacterial culture of sputum

Quantitative cultures were processed within 4 h of collection at the Special Microbiology Laboratory at the Children’s Hospital of Eastern Ontario as per Burns et al. using serial dilution [21]. Diluted samples were inoculated onto MacConkey agar and Pseudomonas Cetrimide Agar. The number of colony forming units (CFU) per milliliter (ml) of sputum was determined by colony counts.

2.3. Nucleic acid extraction for PCR

Sputum samples were diluted 1:10 with sterile Dulbecco’s Phosphate Buffered Saline (D-PBS, 1×), vortexed to mix, and then centrifuged at 11,000 rpm to bring down particulates. Nucleic acids (DNA and RNA) were then extracted from 400 μl of the sputum supernatant using an automated extraction device (iPrep, Life Technologies, Carlsbad, CA) in a final elution volume of 100 μl. The bacteriophage virus MS2 (Zeptometrix Corp., Buffalo, NY) was added to each sample prior to nucleic acid extraction as an amplification and extraction control.

2.4. Real-time PCR for P. aeruginosa

A previously published 5’ exonuclease probe assay targeting the P. aeruginosa ecfX (extra cytoplasmic function sigma factor) was used to detect P. aeruginosa in the sputum samples by real-time PCR [22].

PCR was performed in 10 μl volumes in 96-well PCR plates using TaqMan Fast Advanced master mix (Life Technologies). Thermocycling was performed using a ViiA7 thermocycler (Life Technologies) in a fast mode, with an initial 20 seconds (s) at 95 °C followed by 40 cycles of two-temperature cycling at 95 °C for 3 s, followed by 60 °C for 30 s. Cycle threshold (Ct) values were obtained using the ViiA7 software, and then exported to Excel for analysis.

2.5. PCR for detection of viruses

A real-time PCR and RT-qPCR panel was used to test NP swabs and sputum samples for all major viral respiratory pathogens including: rhinoviruses, enteroviruses, influenza A and B, respiratory syncytial virus (RSV) A and B, human metapneumovirus A and B, parainfluenza virus 1, 2, 3, and 4, coronavirus OC43, coronavirus NL63, coronavirus HKU1, coronavirus 229E, bocavirus, and adenoviruses.

RT-qPCR was performed using a panel of 5’ exonuclease probe assays. The performance of these assays has been validated using molecular proficiency testing specimens and clinical samples.
(manuscript submitted for publication to World Journal of Pediatrics). Briefly, each assay was mixed with TaqMan Fast Virus 1-Step master mix (Life Technologies) and the nucleic acid sample was placed in a 10 µl reaction volume in 96-well plates (Life Technologies). Thermocycling was performed using the ViiA7 thermocycler. Initially, a temperature of 50 °C was held for 5 min for reverse transcription, followed by 40 cycles of two-temperature cycling at 95 °C for 3 s, followed by 60 °C for 30 s. Ct values were obtained and exported to Excel for analysis.

### 2.6. Statistical analysis

Colony counts measured by quantitative culture were analyzed using a log₁₀ scale and data were tested for normality. The colony counts and PCR Cₜ at stable, exacerbation, and post exacerbation assessments, were compared using paired t-tests. The colony counts at exacerbation were compared to the stable assessment immediately preceding it. Generalized estimating equation analysis was conducted to compare viral vs. non-viral exacerbations to account for patients who experienced both types of exacerbations. Data are presented as means with 95% confidence intervals. Statistical tests were two sided, and significance of 0.05 was applied.

### 3. Results

Thirty-five patients with chronic *P. aeruginosa* airway infection were enrolled and were followed for an average of 533 ± 102 days. Twenty-two of these patients had a total of 30 exacerbations during the study period; with a maximum of 2 exacerbations per patient. The mean time from the most recent stable visit until exacerbation was 82 ± 65 days, and from exacerbation to post-exacerbation assessment was 115 ± 70 days. Patient demographic information can be found in Table 1.

Signs and symptoms present during the exacerbations, and differences between virus and non-virus associated exacerbations are shown in Fig. 1. All patients fulfilled criteria for a CF exacerbation.

At the time of exacerbation three (10%) patients required hospitalization and were treated with intravenous (IV) antibiotics. An additional 5 (17%) patients were treated with IV antibiotics at home, 19 (63%) were treated with oral antibiotics and 3 (10%) did not require treatment.

Three exacerbations were excluded from the quantitative bacterial sputum density calculations; two patients did not grow *P. aeruginosa* at the time of exacerbation, and one sample had insufficient volume. Fig. 2 illustrates the change in *P. aeruginosa* bacterial density in sputum collected during stable, pulmonary exacerbation, and post-exacerbation assessments via quantitative culture. There was no significant change in colony counts from stable state to exacerbation; the mean within-patient difference was 0.014 log₁₀ CFU/ml (95% CI −0.51 to 0.53, p = 0.95).

There was similarly no significant change in *P. aeruginosa* sputum density from steady state to exacerbation as measured by PCR. The mean change in Cₜ was −0.31 cycles (95% CI −1.35 to 0.73, p = 0.56) where a negative value indicates a higher bacterial density in the exacerbation sample than in the stable sample.

There was no significant change in bacterial density from exacerbation to post-exacerbation state. The mean within patient change in sputum density from exacerbation to the post-exacerbation visit was 0.20 log₁₀ CFU/ml (95% CI −0.47 to 0.86) (p = 0.57). Seven patients did not return for post-exacerbation assessments and were excluded from this analysis.

Statistical analysis comparing changes in sputum bacterial density by quantitative culture against changes in nucleic acid detection by quantitative PCR showed a moderate correlation (Pearson Correlation Coefficient 0.38, p = 0.048).

Thirty exacerbations had paired sputum taken at baseline and at the time of exacerbation for analysis of viral infection. At baseline, we could only detect viral DNA/RNA by RT-qPCR in the sputum from one stable state sputum sample (coronavirus HKU1). In contrast at the time of exacerbation, respiratory viruses were detected in the sputum or NP swab from 15 of the 30 exacerbation samples. The viruses detected were rhinovirus (67%), RSV type A (13%), PIV type 3 (7%), corona HKU1 (7%) and corona NL63 (7%). Three viruses were detected in an NP swab only, 6 in the sputum only and 6 were detected in both the NP swab and sputum. The patient who was found to have

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**Table 1** Baseline characteristics of study population.

| Characteristic                  | All enrolled patients N = 35 | Patients with exacerbations N = 22 |
|---------------------------------|------------------------------|-----------------------------------|
| Age (mean ± SD)                 | 32.5 ± 12.6                  | 32 ± 14.1                         |
| Sex, n (%)                      |                              |                                   |
| Female                          | 15 (43)                      | 12 (55)                           |
| Male                            | 20 (57)                      | 10 (45)                           |
| FEV1 (mean % predicted ± SD)    | 56.3 ± 22.4                  | 54.7 ± 21.5                       |
| Mild (≥ 80%) n (%)              | 6 (17)                       | 4 (18)                            |
| Moderate (50–79%) n (%)         | 15 (43)                      | 7 (32)                            |
| Severe (30–49%) n (%)           | 10 (29)                      | 9 (41)                            |
| Very severe (<30%) n (%)        | 4 (11)                       | 2 (9)                             |
| BMI (mean ± SD)                 | 22.2 ± 3.1                   | 21.4 ± 5.4                        |
| Medications, n (%)              |                              |                                   |
| • Inhaled tobramycin*           | 26 (74)                      | 18 (82)                           |
| • Dornase alpha                 | 10 (29)                      | 6 (27)                            |
| • Inhaled colistin              | 3 (9)                        | 3 (14)                            |
| • Azithromycin                  | 23 (66)                      | 16 (73)                           |
| Comorbidities, n (%)            |                              |                                   |
| • CF-related diabetes           | 7 (20)                       | 5 (23)                            |
| • Pancreatic insufficiency       | 34 (97)                      | 21 (95)                           |
| • Liver disease                 | 5 (14)                       | 3 (14)                            |
| Colonized bacteria, n (%)       |                              |                                   |
| • P. aeruginosa                 | 35 (100)                     | 22 (100)                          |
| • S. aureus                     | 10 (29)                      | 2 (9)                             |
| • B. cepacia                    | 0                            | 0                                 |
| • H. influenzae                 | 0                            | 0                                 |
| • S. maltophilia               | 0                            | 1 (5)                             |
| • Aspergillus species           | 1 (3)                        | 1 (5)                             |
| • Other                         | 3 (9)                        | 2 (9)                             |
| Mean bacterial density of *P. aeruginosa* during stable period (CFU/ml) | 5.75 × 10⁶ | 6.1 × 10⁶ |

*Inhaled tobramycin may represent inhaled tobramycin, TOBI inhalational solution or TOBI podhaler.*
coronavirus HKU1 at stable state did not have coronavirus or any other virus detected at the time of his exacerbation.

Subgroup analysis showed that there was no significant difference in the change in \textit{P. aeruginosa} sputum density between viral and non-viral exacerbations when measured by quantitative culture and PCR (Figs. 3 and 4). By quantitative culture, the difference in the average change in colony counts of \textit{P. aeruginosa} was 0.59 log\textsubscript{10} CFU/ml (95% CI −0.51 to 1.68;
between the viral and non-viral groups. By PCR Ct value comparison, the mean between-group difference was 1.15 cycles (95% CI −1.03 to 3.38; p = 0.33).

4. Discussion

The results of our study suggest that bacterial density of *P. aeruginosa* is not increased when patients present with a CF exacerbation compared to when they are in a stable state. While respiratory viruses were commonly detected during CF exacerbations, those exacerbations associated with viral infections were not characterized by greater changes in bacterial density of *P. aeruginosa* compared to non-viral associated exacerbations.

To date, few studies have investigated whether sputum bacterial density increases at the time of CF exacerbation. To our knowledge, three studies have been published recently that also addressed this question. The first, by Stressman et al., measured the bacterial density of *P. aeruginosa* at the time of exacerbation and weekly for three weeks prior. They found no change in sputum bacterial density [23]. The second publication by Carmody et al. found no change in total or *P. aeruginosa* bacterial density in the sputum between steady state and exacerbation where the mean time between these states was 84 days [24]. Lastly, Fothergill et al. measured the sputum bacterial density of *P. aeruginosa* by qPCR in 10 patients over a two-year period. At the time of exacerbation, the sputum bacterial density of *P. aeruginosa* did not consistently change [25].

Post-exacerbation bacterial density of *P. aeruginosa* in sputum has been found to be decreased in multiple studies [7–12]. In Ordoñez et al., the density of *P. aeruginosa* in sputum decreased by $2.4 \pm 3.1 \log_{10} \text{CFU/g}$ after 14 days of antibiotics [7]. These results are consistent with a study published by Tunney et al. which found that sputum bacterial density of *P. aeruginosa* decreased by 89% immediately following antibiotic therapy, and returned to baseline levels 137 days later [8]. Finally, in a study published by Regelmann et al., parenteral antibiotic therapy resulted in a significant decrease in the sputum density of *P. aeruginosa*. However, 2 weeks after therapy was discontinued, the sputum density of *P. aeruginosa* was the same as at the time of acute exacerbation [9]. The combination of these studies, and ours, which measured bacterial density an average of 115 days post-exacerbation and showed no change compared to the time of exacerbation, provides evidence that the decrease in bacterial density in the sputum of CF patients associated with antibiotic therapy for exacerbation is a transient phenomenon.

The second question we sought to answer with this study was whether the presence of a viral infection at the time of CF exacerbation influences the bacterial density in sputum. Viruses are well recognized as triggers of exacerbations of airway diseases including COPD, asthma, and CF [13–19,26]. The frequency of virus associated exacerbations in our study was 50%. While somewhat higher than previously reported, this is
consistent with other studies that used sensitive viral PCR detection techniques [27].

In a study performed by Wark et al. of 17 adult patients with CF (13 of whom were chronically infected with \textit{P. aeruginosa}), sputum bacterial density increased slightly but significantly, by a one-fold log change, during exacerbations triggered by viruses when compared to baseline, whereas no changes in sputum bacterial density were seen in non-viral associated exacerbations [13]. Our study did not show the same result. In our study, there was a statistically insignificant 0.58-log difference in the change in sputum density of \textit{P. aeruginosa} when comparing virus associated exacerbations to those not associated with viruses, and in contrast to the Wark study, non-viral exacerbations exhibited a trend to greater increases in sputum density comparatively. In both studies rhinovirus was the most frequent virus implicated. The reasons for the different results seen in these two studies might be due to differences in bacteria; our study was limited to patients chronically infected with \textit{P. aeruginosa}, whereas the Wark study was not. Differing results may also be explained by the differences in severity of exacerbations studied or imprecision related to relatively small sample sizes.

Our study has a few limitations. The first is a relatively small sample size which may have impeded our ability to detect a significant change in bacterial density during pulmonary exacerbations, as well as a difference in those exacerbations that were associated with viruses. The second is that the effects of viral infection on bacterial proliferation might be delayed and occur days after exacerbations present clinically. In patients with COPD infected with rhinovirus, peak bacterial density was on day 15 following infection. These rhinovirus-associated COPD exacerbations were mild in severity, and these patients were not treated with corticosteroids or antibiotics [19]. In CF exacerbations the possibility of delayed bacterial proliferation following a virus-associated exacerbation would be difficult to investigate since antibiotics are a standard therapy at presentation and are rarely withheld. Finally, while viruses do not appear to affect the sputum density of \textit{P. aeruginosa}, this does not preclude other pathogen–pathogen interactions such as effects of viral infections on bacterial phenotype and expression of bacterial virulence factors. For example, in a study where human CF bronchial cells were co-infected with RSV and \textit{P. aeruginosa}, direct binding of RSV to \textit{P. aeruginosa} was observed, and \textit{P. aeruginosa} was found to exhibit increased adherence to human CF cells in vitro in the presence of RSV [28]. Such interactions were not investigated in our study, and further research on viral–bacterial interactions in CF lung disease is needed.

A final potential limitation is that some of the patients included in our study experienced mild pulmonary exacerbations. Interestingly, in a study by Reid et al., while the majority of patients improved clinically with antibiotics, those patients with a decrease in their sputum density of \textit{P. aeruginosa} upon completion of treatment were found to have the greatest

Fig. 4. Comparison of the change in \textit{P. aeruginosa} PCR cycle threshold from stable to exacerbation states, in viral and non-viral exacerbations. Mean change (red bar) for non-viral exacerbations was 0.22 cycles (95% CI −1.06 to 1.50); mean change for viral exacerbations was −0.92 cycles (95% CI −2.64 to 0.80).
improvement in their lung function [12]. One hypothesis generated from this finding might be that the changes to bacterial sputum density are greater with more severe exacerbations and might explain why we did not observe a change with the inclusion of mild exacerbations.

5. Conclusion

In conclusion, our study did not show evidence of significant changes in sputum density of P. aeruginosa at the time of CF exacerbation compared to the stable state. Although 50% of exacerbations were associated with a viral respiratory tract infection, viral infections had no acute effect on changes in P. aeruginosa sputum bacterial density. Given the significance of CF exacerbations, further work is needed to determine if viral infections elicit an immune response that leads to exacerbation that may be independent of P. aeruginosa bacterial load in CF patients [29]. As well, further investigation is required to understand the etiology of exacerbations in patients who do not have viral infections, since increased P. aeruginosa bacterial density in sputum does not appear to be responsible.

Competing interests

None of the authors have any competing interests.

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Author contributions

S.D.A., R.S., and T.F.M. contributed to the conception and design of this study. S.D.A., K.L.V., R.S., E.G., L.H., F.C., and W.F. contributed to the acquisition of data. S.D.A., R.S., M.C., M.D.Z. and R.M. contributed to the analysis and interpretation of data. M.C., M.D.Z. and S.D.A. drafted the manuscript, and all authors critically revised it for important intellectual content and approved the final version to be submitted.

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References

[1] Goss CH, Burns JL. Exacerbations in cystic fibrosis 1: epidemiology and pathogenesis. Thorax 2007;62(4):360–7.
[2] Britto MT, Kotagal UR, Hormung RW, Atherton HD, Tsevat J, Wilmott RW. Impact of recent pulmonary exacerbations on quality of life in patients with cystic fibrosis. Chest 2002;121(1):64–72.
[3] De Boer K, Vandemheen KL, Tullis E, Doucette S, Fergusson D, Freitag A, et al. Exacerbation frequency and clinical outcomes in adult patients with cystic fibrosis. Thorax 2011;66(8):680–5. http://dx.doi.org/10.1136/thx.2011.161117.
[4] Robson M, Abbott J, Webb K, Dodd M, Walsworth-Bell J. A cost description of an adult cystic fibrosis unit and cost analyses of different categories of patients. Thorax 1992;47(9):684–9.
[5] Aaron SD, Ramotar K, Ferris W, Vandemheen K, Saginur R, Tullis E, et al. Adult cystic fibrosis exacerbations and new strains of Pseudomonas aeruginosa. Am J Respir Crit Care Med 2004;169(7):811–5.
[6] VanDevanter DR, Van Dalen JM. How much do Pseudomonas biofilms contribute to symptoms of pulmonary exacerbation in cystic fibrosis? Pediatr Pulm 2005;39(6):504–6.
[7] Ordoñez CL, Henig NR, Mayer-Hamblett N, Accurso FJ, Burns JL, Chmiel JF, et al. Inflammatory and microbiologic markers in induced sputum after intravenous antibiotics in cystic fibrosis. Am J Respir Crit Care Med 2003;168(12):1471–5.
[8] Tunney MM, Klem ER, Fodor AA, Gilpin DF, Moriarty TF, McGrath SJ, et al. Use of culture and molecular analysis to determine the effect of antibiotic treatment on microbial community diversity and abundance during exacerbation in patients with cystic fibrosis. Thorax 2011;66(7):579–84. http://dx.doi.org/10.1136/thx.2010.137281.
[9] Regelmann WE, Elliott GR, Warwick WJ, Clawson CC. Reduction of sputum Pseudomonas aeruginosa density by antibiotics improves lung function in cystic fibrosis more than do bronchodilators and chest physiotherapy alone. Am Rev Respir Dis 1990;141(4 Pt 1):914–21.
[10] Smith AL, Redding G, Doershuk C, Goldmann D, Gore E, Hilman B, et al. Sputum changes associated with therapy for endobronchial exacerbation in cystic fibrosis. J Pediatr 1988;112(4):547–54.
[11] Aaron SD, Vandemheen K, Ferris W, Fergusson D, Tullis E, Haase D, et al. Combination antibiotic susceptibility testing to treat exacerbations of cystic fibrosis associated with multiresistant bacteria: a randomized, double-blind controlled clinical trial. Lancet 2005;366(9484):463–71.
[12] Reid DW, Latham R, Lamont IL, Camara M, Roddam LF. Molecular analysis of changes in Pseudomonas aeruginosa load during treatment of a pulmonary exacerbation in cystic fibrosis. J Cyst Fibros 2013 Dec;12(6):688–99. http://dx.doi.org/10.1016/j.jcf.2013.03.008.
[13] Wark PA, Toore M, Cheese L, Whitehead B, Gibson PG, Wark KF, et al. Viral infections trigger exacerbations of cystic fibrosis in adults and children. Eur Respir J 2012;40(2):510–2. http://dx.doi.org/10.1183/09031998.0020311.
[14] Wat D, Gelder C, Hibbitts S, Cafferty F, Bowler I, Pierrepont M, et al. The role of respiratory viruses in cystic fibrosis. J Cyst Fibros 2008;7(4):320–8. http://dx.doi.org/10.1016/j.jcf.2007.12.002.
[15] Etherington C, Naseer R, Conway SP, Whitaker P, Denton M, Peckham DG. The role of respiratory viruses in adult patients with cystic fibrosis receiving intravenous antibiotics for a pulmonary exacerbation. J Cyst Fibros 2014;13(1):49–55. http://dx.doi.org/10.1016/j.jcf.2013.06.004.
[16] Fliglt WG, Bright-Thomas RJ, Tilston P, Mutton KJ, Guiver M, Morris J, et al. Incidence and clinical impact of respiratory viruses in adults with cystic fibrosis. Thorax 2014;69(3):247–53. http://dx.doi.org/10.1136/thoraxjnl-2013-204000.
[17] Smyth AR, Smyth RL, Tong CY, Hart CA, Heaf DP. Effect of respiratory virus infections including rhinovirus on clinical status in cystic fibrosis. Arch Dis Child 1995;73(2):117–20.
[18] Mallia P, Footitt J, Sotero R, Jepson A, Contoli M, Trujillo-Torralbo MB, et al. Rhinovirus infection induces degradation of antimicrobial peptides and secondary bacterial infection in COPD. Am J Respir Crit Care Med 2012;186(11):1117–24. http://dx.doi.org/10.1164/rccm.201205-0806OC.
[19] Molyneaux PL, Mallia P, Cox MJ, Footitt J, Willis-Owen SA, Homola D, et al. Outgrowth of the bacterial airway microbiome after rhinovirus exacerbation of chronic obstructive pulmonary disease. Am J Respir Crit Care Med 2013;188(10):1224–31. http://dx.doi.org/10.1164/rccm.201302-0314OC.
[20] Cystic Fibrosis Foundation. Microbiology and infectious disease in cystic fibrosis: Cystic Fibrosis Foundation; 1994 1–26.
[21] Burns JL, Emerson J, Stapp JR, Yim DL, Krzewinski J, Louden L, et al. Microbiology of sputum from patients at cystic fibrosis centers in the United States. Clin Infect Dis 1998 Jul;27(1):158–63.
[22] Anuj SN, Whiley DM, Kidd TJ, Bell SC, Wainwright CE, Nissen MD, et al. Identification of Pseudomonas aeruginosa by a duplex real-time polymerase chain reaction assay targeting the ecfX and the gyrB genes. Diagn Microbiol Infect Dis 2009 Feb;63(2):127–31. http://dx.doi.org/10.1016/j.diagmicrobio.2008.09.018.
[23] Stressmann FA, Rogers GB, Marsh P, Lilley AK, Daniels TW, Carroll MP, et al. Does bacterial density in cystic fibrosis sputum increase prior to pulmonary exacerbation? J Cyst Fibros 2011;10(5):357–65. http://dx.doi.org/10.1016/j.jcf.2011.05.002.

[24] Carmody LA, Zhao J, Schloss PD, Petrosino JF, Murray S, Young VB, et al. Changes in cystic fibrosis airway microbiota at pulmonary exacerbation. Annu Am Thorac Soc 2013;10(3):179–87. http://dx.doi.org/10.1513/AnnalsATS.201211-107OC.

[25] Fothergill JL, Ledson MJ, Walsh MJ, McNamara PS, Southern KW, Winstanley C. Comparison of real time diagnostic chemistries to detect Pseudomonas aeruginosa in respiratory samples from cystic fibrosis patients. J Cyst Fibros 2013 Dec;12(6):675–81. http://dx.doi.org/10.1016/j.jcf.2013.04.007.

[26] Yamaya M. Virus infection-induced bronchial asthma exacerbation. Pulm Med 2012;2012:834826. http://dx.doi.org/10.1155/2012/834826.

[27] Singanayagam A, Joshi PV, Mallia P, Johnston SL. Viruses exacerbating chronic pulmonary disease: the role of immune modulation. BMC Med 2012;10:27. http://dx.doi.org/10.1186/1741-7015-10-27.

[28] Van Ewijk BE, Wolfs TF, Aerts PC, Van Kessel KP, Fleer A, Kimpen JL, et al. RSV mediates Pseudomonas aeruginosa binding to cystic fibrosis and normal epithelial cells. Pediatr Res 2007 Apr;61(4):398–403.

[29] Ramirez IA, Caverly LL, Kalikin LM, Goldsmith AM, Lewis TC, Burke DT, et al. Differential responses to rhinovirus- and influenza-associated pulmonary exacerbations in patients with cystic fibrosis. Annu Am Thorac Soc 2014 May;11(4):554–61. http://dx.doi.org/10.1513/AnnalsATS.201310-346OC.