People with the genetic condition cystic fibrosis suffer repeated respiratory tract infections from an early age, which are often superseded by chronic airway infection, with resultant progressive loss of lung function and premature death from respiratory failure. Acute pulmonary exacerbations contribute to diminished quality of life, reduced lung function, morbidity and mortality in cystic fibrosis, and remain a major obstacle to improving long term outcomes. This article discusses current diagnostic and therapeutic strategies employed in the treatment of pulmonary exacerbations, with a focus on critical appraisal of the evidence based on which strategies are founded. Areas of uncertainty are highlighted and current and potential future research directions are discussed.

**KEYWORDS:** antibiotics, cystic fibrosis, definition, etiology, infection, treatment

Advances in cystic fibrosis (CF) care, including better nutrition, aggressive treatment of infection, and the development of specialist center care, have led to substantial improvements in life expectancy [8]. However, the majority of patients still die from complications associated with chronic respiratory sepsis before their fifth decade of life. Equally, improvements in survival have come at the cost of treatment-related morbidity including the emergence of multidrug resistant infections, complications of indwelling intravenous lines, and allergic and toxic effects of antibiotics [2–4]. Awareness of the potential pitfalls of treatment places the onus on the treating CF team to ensure that therapies are used in a way that maximizes their effect, while minimizing exposure to harm.

Pulmonary exacerbations are characterized by increasing respiratory symptoms and acute deterioration of lung function. They are associated with significant morbidity and mortality and may accelerate lung function decline [5,6], as well as being associated with diminished quality of life [7] and increased healthcare costs [8].

The availability of high-quality clinical trials to guide therapy in CF is limited and this is particularly true of exacerbations. Similarly, there have been multiple studies into airway inflammation and bacterial infection during exacerbations, but no therapies have been developed based on new knowledge generated. Thus, treatment decisions are often based on clinical experience and anecdote. Barriers to study design include inadequate cohort sizes to adequately powered single center trials, limited pharmaceutical industry investment in multicenter studies, and differences in study designs required to satisfy drug licensing authorities internationally.

The aim of this article is to critically appraise the current evidence base on which strategies for treatment of pulmonary exacerbations are founded, and discuss how treatment is commonly implemented where evidence is lacking. We highlight current areas of uncertainty, and propose areas in which further research is required.

**Defining an exacerbation**

In 1994 the Cystic Fibrosis Foundation (USA) convened a consensus conference to define outcome measures for use in CF clinical trials [9]. One of the eight ‘top priority’ issues identified was the development of a standard definition of a pulmonary exacerbation that could be applied consistently within clinical trials. Despite this welcome initiative, 17 years later no universally accepted definition has been realized. The development of an exacerbation definition is con-founded by the natural day-to-day variability of symptoms, poor correlation between biomarkers and clinical outcomes [10], and differences in hospital admission and antibiotic administration policies between CF centers and across healthcare settings [11].

The absence of a universally accepted definition of what constitutes an exacerbation makes direct comparison between rates and severity of pulmonary exacerbations reported in clinical trials difficult. Other important uses of a definition include the ability to track changes in disease...
epidemiology, and their utility as decision aids with respect to determining when treatment of an exacerbation can be safely discontinued.

In attempting to formulate a standard definition of pulmonary exacerbations, several authors have adopted the approach of performing component analysis of previous studies to examine for the factors most likely to prompt the treating physician to make the diagnosis of an exacerbation [12–14]. In these studies, symptoms generally outperformed physical examination findings and investigations. Increased cough, and increased sputum volume or purulence, and decreased appetite and weight were found to be most predictive (Table 1). The findings of these studies have not been incorporated into a unifying definition and instead, multiple different and invalidated scoring systems remain the norm [15,16].

A fall in lung function is usually seen during a pulmonary exacerbation, therefore incorporating spirometric measures into the definition of a pulmonary exacerbation may be reasonable. However, in up to a quarter of patients lung function fails to return to baseline by the end of treatment suggesting its use in guiding treatment duration may be limited [17].

Given the hypothesis that exacerbations are precipitated by an imbalance between host immunity and infection, research has, and continues to focus on identifying biomarkers capable of detecting exacerbation onset and recovery. The ideal biomarker of exacerbations should maintain its sensitivity with varying disease severity, be minimally impacted on by independent factors (e.g., age and sex), and respond rapidly with clinical improvement and resolution of inflammation [10].

Table 1. Symptom profiles used in previous attempts to define a pulmonary exacerbation.

<table>
<thead>
<tr>
<th>Signs and symptoms (new or increased)</th>
<th>Fuchs</th>
<th>Ramsey</th>
<th>ARIC</th>
<th>RSSQ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pulmonary signs and symptoms</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased dyspnoea with exertion</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Decreased exercise tolerance</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased work of breath</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cough</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day cough</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Night cough</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet or congested cough</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chest congestion</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency of cough</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cough up mucus</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheezing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemoptysis/coughing up blood</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sputum volume</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Change in sputum appearance</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Change in sputum colour</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Change in sputum consistency</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Increased respiratory rate</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Decreased lung function</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Upper respiratory tract symptoms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sore throat/runny nose</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinus pain/tenderness</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Change in sinus discharge</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Constitutional and GI signs and symptoms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malaise/fatigue/lethargy</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abdominal pain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fever</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased appetite/anorexia</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Weight loss</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work/school absenteeism</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

ARIC: Acute Respiratory Illness Checklist; RSSQ: Respiratory and Systemic Questionnaire (© BoehringerIngelheim). Reproduced with permission from [42].
Levels of the acute phase reactant, C-reactive protein (CRP), increase in the presence of systemic inflammation, and in particular in the setting of bacterial infections. In CF, CRP levels often increase at the onset of an exacerbation, and decrease with the administration of antibiotics [18,19]. However CRP levels have been shown to return to normal before an improvement in either clinical status or lung function is seen, suggesting it has limited utility as a guide to discontinuation of therapy [20]. Furthermore, changes in CRP with treatment vary widely between individuals, and have even been shown to increase in some patients despite clinical response [20].

Airway inflammation in CF is neutrophil predominant [21]. The chemokine IL-8 is a major neutrophil chemoattractant, and can be detected in high levels in CF sputum [18]. Studies have demonstrated a fall in sputum IL-8 levels in response to antibiotic therapy, and a correlation with improvement in lung function [18]. However, results have been inconsistent, both between studies and between individuals within studies [10,19,22]. This variability may reflect differing sampling techniques (induced vs expectorated sputum) and the response of IL-8 may depend on the degree of disease severity (i.e., less reduction in IL-8 in the setting of more advanced lung disease). Another confounding factor is the anatomical heterogeneity in lung disease and difference in sputum purulence depending on sample origin within the lung. Similar difficulties have been found with a range of other pro- and anti-inflammatory cytokines (including IL-6, IL-10, TNF-α) and neutrophil products (including neutrophils elastase complexes and myeloperoxidase) that have been assessed as biomarkers [10,22].

Neutrophil elastase (NE) is a proteolytic enzyme released by activated neutrophils that is believed to contribute to host tissue damage at sites of inflammation. Neutrophils derived from patients with CF spontaneously release increased amounts of NE, and NE can be detected in high concentrations in airway secretions [10,23]. A number of studies have reported a fall in NE in response to treatment of an exacerbation, but again results between studies have not been consistent [23,24]. Calprotectin is also produced by activated neutrophils in response to pro-inflammatory cytokines and has been validated as a fecal marker of inflammatory bowel disease [25], but it is also detectable in CF serum and airway secretions. A recent study has demonstrated decreases in sputum and serum calprotectin levels with treatment of pulmonary exacerbations and changes in sputum calprotectin demonstrated a stronger correlation with clinical improvement when compared with IL-8, VEGF or myeloperoxidase [19]. Future studies will delineate whether this marker will prove to be more specific than its predecessors.

Exhaled breath condensates (EBC) measure volatile substances that are produced in the lungs and appear in expired air. They have potential advantages over sputum sampling by providing a summated assessment of the lung, and can be measured in both young children, and patients unable to produce expectorated sputum samples. The reported differences in EBC from CF patients when compared with healthy controls include lower pH, nitric oxide and ammonia concentrations, and increased concentrations of IL-6, IL-8, leukotriene B4 and nitrates [26–30]. However, as with sputum biomarkers, reported changes during exacerbations and their treatment have been inconsistent [27–29].

An alternate approach to measuring the inflammatory response is to measure changes in airway microbial flora. At the most basic level this can be achieved by determining sputum bacterial concentrations before and after treatment. When this has been done most studies report a fall in bacterial load accompanying clinical improvement [31]. However, airway infection in CF is polymicrobial [32], and it is still not known which organisms are the most important during exacerbations, and consequently which should be monitored to indicate response [33].

In the setting of chronic bacterial infection, the growth of subpopulations of bacteria with increased virulence may also be important. Detection of either these subpopulations or the virulence factors that they produce may facilitate diagnosis of exacerbations. *Pseudomonas aeruginosa* (the major pathogen of chronic CF airways infection) is capable of rapid changes in both genotype and phenotype during exacerbations [34]. Potential indicators of *P. aeruginosa* virulence detectable in CF sputum and EBC include pyocyanin, quorum sensing (QS) signals, exotoxins and pyoverdine, as well as the appearance of *P. aeruginosa* small colony variants [35–38]. There are currently only limited clinical data to support the use of virulence factors to monitor response. Grimwood et al. demonstrated an increased concentration of *P. aeruginosa* exo-enzymes in CF patients’ sputum during acute exacerbations compared with stable controls, and that concentrations fell in response to antibiotics [39]. In a more recent study, Fothergill
et al. examined a panel of P. aeruginosa virulence factors and described differing patterns of response to antibiotics in each of the three patients studied [34].

Future perspective
Future research will need to focus on longitudinal studies correlating biomarkers with changes in lung function, symptoms and antibiotic response. It is unlikely that a single biomarker will be pathognomonic of a pulmonary exacerbation. However, it may be possible to develop a panel of markers that will increase diagnostic certainty and the ability to monitor the response of host and pathogen to treatment more reliably.

Epidemiology & impact of exacerbations
Data from patient registries demonstrate that the proportion of patients requiring intravenous antibiotics and hospital admissions for respiratory exacerbations increases with age, and is mirrored by a decline in lung function [40–42]. These findings are further supported by data from the Epidemiological Study of CF (ESCF), which reported that the rate of intravenous antibiotic use (at least one course per year) increased from only 23% in those aged under 6 years to 63% of patients aged over 18 years [14].

Pulmonary exacerbations have a significant impact on long-term lung health, with 25% of patients who suffer a pulmonary exacerbation failing to recover their baseline lung function following intravenous antibiotic treatment [17]. Furthermore children having a single, and adults having greater than three exacerbations in a year experience an accelerated decline in lung function in the subsequent three years (6). These data are supported by a model predicting 5-year survival in CF, which demonstrated that each pulmonary exacerbation experienced annually was equivalent to a reduction in FEV1 predicted of 12% (5). Other impacts of exacerbations include an increased need for domiciliary oxygen, non-invasive ventilation and diminished health-related quality of life [7,43]. Severe pulmonary exacerbations necessitating intensive care unit (ICU) admission are associated with increased mortality, with in-hospital survival rates as low as 27% in patients requiring invasive ventilator support [43,44].

Given the clinical impact of pulmonary exacerbations in CF identification of factors that may predispose to their occurrence are important in planning preventative strategies. However, to date only one prospective study has examined factors that predict pulmonary exacerbations [45]. This study, performed in a cohort of patients chronically infected with multidrug resistant organisms (e.g., P. aeruginosa, Burkholderia spp) identified female sex, poor lung function, previous pulmonary exacerbations, and the use of inhaled corticosteroids as potential risk factors. Interestingly, a negative correlation between age and exacerbations was demonstrated, which the authors postulated may represent a survivor effect. A recent post-hoc analysis of data from the ESCF including 16,000 patients similarly identified decreased lung function, female sex, and previous exacerbations, as well as P. aeruginosa infection as significant risk factors for exacerbations regardless of age [46]. Other risk factors identified from smaller retrospective studies include, low socioeconomic status and acute viral infection [47–49].

Etiology of exacerbations
Pulmonary inflammation and infection begins a short time after birth [50,51]. Initial intermittent infection is often followed by the establishment of chronic infection, often with Gram-negative bacteria. Factors predisposing to the establishment of chronic infection are beyond the scope of this article, but excellent reviews of this topic are available [51,52].

Once chronic infection is established a vicious cycle of infection and inflammation develops and acute pulmonary exacerbations are presumed to occur when this balance is perturbed. Proposed mechanisms for the development of an exacerbation include acute respiratory viral infections, acquisition of a new bacterial strain, a change in the resident bacterial flora, or an acute increase in airway inflammation – potentially as a consequence of altered host immunity.

Virus induced exacerbations
An association between viral infections and pulmonary deterioration in CF was first described over 25 years ago [53]. In this sentinel study of children with CF, isolation of a virus at the time of a pulmonary exacerbation resulted in accelerated progression of lung disease. In subsequent studies, rates of viral isolation at the times of pulmonary exacerbations of between 9% and 46% have been described [48,54,55], with the highest reported rates in those studies that have used molecular detection techniques.

The viruses detected depend on the sampling technique (nasopharyngeal aspirate compared with cough swab and bronchoalveolar lavage) and the age of the study population. However,
the viruses are in general similar to those seen in people without CF, with rhinovirus, respiratory syncytial virus (RSV), influenza A and B, and para-influenza virus IV being the most commonly detected [48,54,55].

Debate exists about whether viruses trigger exacerbations in their own right, or act indirectly by increasing the virulence of existing airway bacteria. Possible mechanistic links between viral infection and bacterial virulence include virus-induced reduction in alveolar macrophage antibacterial responses and facilitation of bacterial binding to epithelial cells [56,57]. However other authors highlight the poor correlation between viral infection and increased bacterial number to argue that viruses have direct effects on airway inflammation [48]. There is also evidence that the anatomical site of viral infection within the airway may be important, for example lower respiratory tract viruses (including RSV and influenza) may influence the rate of lung function decline, whereas upper respiratory tract viruses (including rhinoviruses) appear to have less impact [59].

In 2009 the emergence of the first influenza pandemic to occur in the modern era of CF care gave an insight into how a novel viral infection may affect people with CF. Initial single center reports in the wake of the pandemic from Australia and UK reported that in general patients had mild clinical course [58,59]. Subsequently a large multinational study (24 European centers, one USA center) reported the outcomes in 110 cases from an at-risk population of greater than 4500 (incidence 2.3%). While most patients again suffered a self-limiting illness with a return to baseline lung function within 30 days of infection, there was significant short-term morbidity with two thirds requiring intravenous antibiotics and 50% being admitted to hospital. Patients with severe lung function impairment prior to infection were most severely affected, with six patients in this group requiring ICU admission and three dying [60].

Further work is required to delineate the pathogenic potential of specific viruses, including to determine the optimum sampling site and processing technique for diagnosis, and to investigate the role of antiviral agents in treatment of pulmonary exacerbations.

The role of chronic P. aeruginosa infection in exacerbations

By the age of 18 years, 80% of patients with CF will have chronic infection with P. aeruginosa [40,41]. Following its establishment, P. aeruginosa undergoes phenotypic and genetic adaptations that support persistent infection [61]. Arguably the most important of these is the transformation from a planktonic free-living state, to a ‘mucoid’ phenotype typified by the production of alginate, and the formation of bacterial communities encased within a ‘biofilm’ of extracellular glycoproteins. Such changes offer protection from host immune defenses and limit antibiotic penetration [62]. Biofilm dwelling bacteria are not eradicated by the host immune response, but their presence probably provides stimulus for chronic inflammation.

Biofilm dwelling bacteria employ density dependent cell-to-cell communication (QS) to ensure survival of the colony within the constraints of its environment. It has been proposed that relatively inert biofilms periodically expel colonies of immunogenic planktonic bacteria in response to environmental stimuli, which can induce an acute exacerbation [63]. This theory is supported by data showing that in 94% of patients with chronic P. aeruginosa infection the same strain is isolated during periods of clinical stability and acute exacerbations [64].

Culture negative exacerbations

In 20% of pulmonary exacerbations the typical bacteria of the CF airway are not detected, particularly in children [65]. Although some exacerbations may be caused by viruses, the etiology of the remainder are unexplained. Recent interest has focused on anaerobic bacterial pathogens as the polymicrobial nature of infection in the CF lung becomes apparent [32]. Thick mucus within the airways creates anaerobic and microaerobic niches and studies utilizing anaerobic culture and nonculture molecular techniques have provided compelling evidence that CF airways are chronically infected with anaerobic bacteria [32,33,66]. A number of the anaerobes that have been detected are known pulmonary pathogens responsible for nosocomial pneumonia and lung abscesses [67,68]. It is therefore possible that anaerobes, which are not detected by standard sputum culture techniques, play an important role in triggering pulmonary exacerbations. More studies are required to assess the clinical impact of anaerobes in the CF airway [33,69].

Fungi may also have a role in exacerbations. Aspergillus species are isolated in half of all CF sputum samples [70], and allergic bronchopulmonary aspergillosis (ABPA) is relatively common [71]. Although a ‘flare’ of ABPA may mimic a pulmonary exacerbation, it can usually be differentiated by the presence of airway
'casts’, accompanied by elevated blood IgE, peripheral blood eosinophilia, and positive Aspergillus precipitins [71]. However, recent evidence demonstrating an increased rate of lung function decline and pulmonary exacerbations in patients with chronic Aspergillus fumigatus infection, independent of the formal diagnosis of ABPA suggests that airway fungal infection may have a pathogenic role in exacerbations [72].

Gastro-esophageal reflux disease (GORD) is common in CF, occurring in up to half of patients regardless of symptoms or acid suppression treatment [73]. Post lung transplantation, untreated GORD is associated with an increased rate of lung function decline and onset of chronic rejection [74], but its impact in CF prior to transplantation is poorly understood. There is evidence that GORD is associated with increased cough, and lung function decline [73], but the role of GORD in provoking exacerbations has not been studied. In CF patients who are ‘frequent exacerbators’, GORD may be an important contributor and should be actively sought and treated when present. Use of acid suppression treatment may neutralize the pH of fluid aspirated, but may also inadvertently increase the microbial burden of gastric fluid aspirated [75]. Further research is needed in this area, but early surgical fundoplication may be the preferred option when it can be performed safely [76].

Future perspective

Much is still unknown about the etiology of pulmonary exacerbations in CF. Future research will focus on identifying mechanisms by which infectious and noninfectious stimuli trigger an increase in the host immune response in order to identify common pathways that may be manipulated to reduce airway inflammation and remodeling.

The role of sputum microbiology in guiding the treatment of exacerbations

Traditional sputum microbiological techniques for routine CF respiratory samples use selective media to specifically culture known pathogenic bacteria, followed by determination of antibiotic susceptibility based on the minimum inhibitory concentration in vitro. When a single organism is responsible for pulmonary infection (e.g., community acquired pneumonia) susceptibility profiles are valuable in guiding antibiotic therapy [77,78]. However, CF pulmonary infection is polymicrobial and using routine culture and sensitivity results as a guide to antibiotic therapy may not be ideal. Culture-independent (metagenomic) microbiological techniques that utilize bacterial RNA present in specimens to generate bacterial profiles, suggest that culture-dependent techniques detect only a minority of the organisms that exist within the infective milieu of CF sputum [79]. Standard culture techniques also under-represent the phenotypic diversity among detected bacteria. Fothergill et al. have recently demonstrated immense heterogeneity in genotype and phenotype (including antibiotic resistance) between apparently identical morphotypes of _P. aeruginosa_ cultured from a single sputum sample [34]. In comparison, current standard microbiological practices would only select a limited number of morphotypes for susceptibility testing, potentially resulting in a resistance profile that misrepresents the _P. aeruginosa_ population as a ‘whole’ in an individual patient.

The efficacy of routine microbiology is also compromised by the difference in behavior of the most common CF pathogen, _P. aeruginosa_ when growing in a biofilm compared with routine pathology laboratory culture systems. For instance biofilm dwelling _P. aeruginosa_ are believed to be up to a 1000-times more resistant to antibiotics than planktonic growing bacteria [80].

These limitations of established antibiotic testing methods most likely explain the poor correlation between conventional susceptibility profiles generated by single agent antibiotic testing, and clinical response to treatment [81]. Interestingly, despite a lack of evidence of improved outcomes most clinical guidelines for CF care still advocate the use of antibiotic sensitivity profiles to select ‘appropriate’ antibiotic regimens [82,83].

Given the shortfalls of traditional single agent sensitivity testing methods a number of alternate strategies are currently being investigated. The recognition that a number of antibiotics exhibit synergistic effects when co-administered _in vitro_, has led to the development of techniques to test the sensitivity of _P. aeruginosa_ to combinations of antibiotics [84]. However, application of these methods to guide clinical practice has been limited, with similar clinical and bacteriological responses observed in patients receiving treatment based on single agent sensitivity testing results compared to multiple combination bactericidal testing in a randomized control trial [85].
In vitro biofilm models for assessment of antibiotic susceptibility have been investigated [86,87]. To date, only one study has reported outcomes in patients with antibiotics selected by such techniques and this study also failed to demonstrate superior clinical or microbiological outcomes using the biofilm model [88]. Reasons for this failure may include the confounding effect of different environmental conditions in the lung that were not replicated within the biofilm model (e.g., oxygen concentration and pH) and the need to also account for the fact that a polymicrobial infection exists in the CF lung.

Future perspective
As we begin to more fully understand the complexity of airway infection in CF it is clear that novel microbiological diagnostic methods are required, which more accurately represent resident flora. The emergence and implementation of metagenomic techniques to characterize the bacterial diversity of airway secretion will hopefully improve our understanding of how polymicrobial infections respond to antibiotic treatment. The application of bioinformatics may also provide greater insight into the expression of bacterial resistance genes on a ‘whole population’ basis that will more accurately predict the response to treatment.

Treating pulmonary exacerbations
Antibiotics are used routinely to treat pulmonary exacerbations in patients with CF, yet this is based on limited evidence including only two small randomized clinical trials [89,90]. Despite neither study providing clear evidence of improved clinical end points in the antibiotic treatment arms, undertaking further placebo-controlled trials would be considered unethical, given the strong anecdotal evidence for benefit.

In selecting an antibiotic regime for an individual patient important considerations include, the specific bacterial pathogens present within the airways, preferred location of treatment (hospital vs home), route of administration, how many antibiotics to use, and which ones to prescribe [91]. These decisions are often influenced by exacerbation severity, available intravenous access, previous antibiotic allergies, adherence and the support available to the individual patient if home-based therapy is to be considered.

Bacteriological considerations
The choice of antibiotics is based on the sensitivity profile of bacteria present on culture of airway secretions. Early infection is typically with the common respiratory pathogen Staphylococcus aureus, and nontypeable Haemophilus influenzae, which are often replaced by P. aeruginosa in late childhood. Other Gram-negative bacteria that may cause chronic infection in a minority of patients include Burkholderia cepacia complex (BCC), Stenotrophomonas maltophilia and Achromobacter xylosoxidans [92].

The realization that chronic P. aeruginosa infection results in increased lung function decline, exacerbation frequency, morbidity and mortality has led to the development of early detection programs that often involve invasive bronchoscopies and aggressive antibiotic regimes aimed at eradicating P. aeruginosa infection at the time of first acquisition [93–96]. Implementation of these regimes within pediatric centers has proven to be effective in delaying the onset of chronic P. aeruginosa infection by several years [96], though their impact on the development of bronchiectasis is not well established [97]. However, the long-term impact on survival, antibiotic resistance profiles, and the potential acquisition of other opportunistic bacterial pathogens is not well understood. Similar strategies have been proposed for first acquisition of other CF airway pathogens, but again the long-term efficacy of these regimens remains to be proven (Table 2).

In recent years an evolution of airway bacterial infection has been witnessed with the emergence of several new opportunistic bacteria including S. maltophilia, A. xylosoxidans, methicillin-resistant S. aureus (MRSA), and other Gram-negative bacteria (e.g., Ralstonia and Pandoraea species), while rates of Burkholderia species infection have remained constant [92]. The explanation for the changing microbial profile is unclear but may include better microbiological detection techniques, the effects of more aggressive and successful treatment of P. aeruginosa, increased prevalence of the opportunistic pathogens within healthcare facilities, or simply a consequence of increased survival leading to selective pressure due to greater lifetime exposure to antibiotic therapy.

Whilst BCC infections are associated with worse clinical outcomes (including reduced post-transplant survival) [98–100], the clinical importance of other Burkholderia species and emerging Gram-negative pathogens are unknown. However, many of these other bacteria are inherently antibiotic resistant, which may increase their potential to significantly impact on disease course and survival in CF [101–103].
In the absence of Gram-negative organisms, antibiotic therapy is directed towards this and modified to target co-infections if clinical response is suboptimal (Table 3).

### Antipseudomonal antibiotic classes

#### Fluoroquinolones

Fluoroquinolones exert their bactericidal effect against Gram-negative bacteria through inhibition of DNA gyrase and remain the only oral agent to which *P. aeruginosa* is susceptible in vitro. Aminoglycosides demonstrate dose-dependent antimicrobial effects, suggesting the peak plasma concentration achieved is the most important pharmacokinetic attribute for bacterial killing. This is supported by studies demonstrating the equivalence of once-daily administration compared with traditional multidose regimes \[104,105\]. The major limitation of systemic aminoglycosides is the potential to develop renal and neuropathy. The potency to remain the only oral agent to which *P. aeruginosa* is susceptible in vitro.

### Additional factors that may limit nephrotoxicity include

- Once-daily dosing regimens
- Morning aminoglycoside dosing \[104\]
- Therefore, despite antibiotic guidelines, typically suggesting a total平稳 plasma levels above the minimal inhibitory concentration, combined with traditional multidose administration, the equivalence of once-daily administration compared with traditional multidose regimes \[104,105\]. The major limitation of systemic aminoglycosides is the potential to develop renal and neuropathy. The potency to remain the only oral agent to which *P. aeruginosa* is susceptible in vitro.

### Table 2. Eradications strategies for treatment of specific airway pathogens at first isolation.

<table>
<thead>
<tr>
<th>Bacteria</th>
<th>Antibiotic</th>
<th>Dose</th>
<th>Special instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methicillin-sensitive <em>Staphylococcus aureus</em></td>
<td>Flucloxacillin</td>
<td>100 mg/kg/day oral</td>
<td>Two agents in combination for 2–4 weeks. If persistent infection consider 2 weeks of combination IV agents</td>
</tr>
<tr>
<td></td>
<td>Fusidic acid</td>
<td>750 mg daily oral prl (=12 years old)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dosing under 12 complicated see PI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methicillin-resistant <em>Staphylococcus aureus</em></td>
<td>Topical mupirocin</td>
<td>Intranasal</td>
<td>Combined use of topical mupirocin (5 days) and two other oral agents for 6 weeks to 6 months</td>
</tr>
<tr>
<td></td>
<td>Trimethoprim–sulfamethoxazol</td>
<td>160/800 mg b.i.d. oral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fusidic acid</td>
<td>750 mg daily oral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dosing under 12 complicated see PI</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rifampicin</td>
<td>10 mg/kg/day oral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max 450 mg under 45 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max 600 mg over 45 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Haemophilus influenzae</em></td>
<td>Amoxicillin–clavulanic acid</td>
<td>875/125 mg b.i.d. oral or</td>
<td>Single agent for 2–4 weeks, repeated if still positive at the end of the course. Consider 2 week IV course if remains positive</td>
</tr>
<tr>
<td></td>
<td>250/125 mg, 2 t.i.d. oral</td>
<td>Dosing under 12 complicated see PI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Doxycycline</td>
<td>200 mg initial dose, 100 mg b.i.d. oral†</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cefadroxil</td>
<td>500 mg t.i.d. (&gt;7 years), 250 mg t.i.d. (1–7 years) oral</td>
<td></td>
</tr>
<tr>
<td>Pseudomonas aeruginosa</td>
<td>Ciprofloxacin</td>
<td>15 mg/kg oral b.i.d. (under 5 years)</td>
<td>3 weeks to 3 months of ciprofloxacin combined with an inhaled antibiotic</td>
</tr>
<tr>
<td></td>
<td>20 mg/kg oral b.i.d. (5–18 years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>750 mg b.i.d. oral (adult)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Colistin</td>
<td>1 million units b.i.d. inhaled (under 2 years)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 million units b.i.d. inhaled (over 2 years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tobramycin</td>
<td>300 mg b.i.d. inhaled</td>
<td></td>
</tr>
</tbody>
</table>

† Avoid tetracyclines in patients under 12 years of age.

b.i.d.: Twice daily; iv.: Intravenous; Max: Maximum dose; PI: Product Information; t.i.d.: Three-times daily.

Data taken from the Report of the UK Cystic Fibrosis Trust Antibiotic Working Group, and the Australian Therapeutic Guidelines \[82,83\].
concentration (MIC) of the bacterial pathogen may be important. This led to the hypothesis that continuous infusions would have greater antibacterial effects than intermittent dosing regimens. However, to date β-lactams delivered by continuous infusion have not proven more efficacious than multiple daily doses [111]. In addition a recent study suggested that twice daily ceftazadime dosing may be equivalent to traditional three-time daily dosing [112], although the study has been criticized for being underpowered [113].

There are several classes of β-lactams including, the extended spectrum penicillins (e.g., ticarcillin and piperacillin) and third generation cephalosporins (ceftazadime), which together are the most extensively studied and widely used first-line agents [114], but are also associated

Table 3. Oral and intravenous antibiotics for the treatment of pulmonary exacerbations where Pseudomonas aeruginosa is not isolated†.

<table>
<thead>
<tr>
<th>Bacteria</th>
<th>Antibiotic</th>
<th>Dose</th>
<th>Special considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oral antibiotics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methicillin-sensitive Staphylococcus aureus</td>
<td>Di/Flucloxacin</td>
<td>125 mg b.i.d. (prophylaxis) 25 mg/kg q.d. (&lt;18 years of age) 1–2 g q.d.</td>
<td>Consider prophylaxis in 0–3 years of age, but currently unproven clinical benefit</td>
</tr>
<tr>
<td></td>
<td>Trimethoprim–sulfamethoxazole</td>
<td>160/800 mg b.i.d.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clindamycin</td>
<td>450 mg t.i.d.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roxithromycin</td>
<td>150 mg b.i.d.</td>
<td></td>
</tr>
<tr>
<td>Stenotrophomonas maltophilia</td>
<td>Trimethoprim–sulfamethoxazole</td>
<td>160/800 mg b.i.d.</td>
<td>Targeted treatment currently of unproven benefit</td>
</tr>
<tr>
<td></td>
<td>Minocycline</td>
<td>200 mg initial dose, 100 mg b.i.d.*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tigecycline</td>
<td>100 mg initial dose, 50 mg b.i.d.*</td>
<td></td>
</tr>
<tr>
<td><strong>Intravenous antibiotics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methicillin-sensitive Staphylococcus aureus</td>
<td>Di/Flucloxacin</td>
<td>50 mg/kg (&lt;18 years) 500 mg to 1 g q.d.</td>
<td></td>
</tr>
<tr>
<td>Methicillin-resistant Staphylococcus aureus</td>
<td>Vancomycin†</td>
<td>1 g b.i.d.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Teicoplanin</td>
<td>10 mg/kg b.i.d. three doses, daily (&lt;18 years) 400 mg for b.i.d. three doses, then daily</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linezolid</td>
<td>10 mg/kg (&lt;12 years) 600 mg daily</td>
<td></td>
</tr>
<tr>
<td>Haemophilus influenzae</td>
<td>Cefuroxime</td>
<td>50 mg/kg t.i.d. (1–18 years old) 1.5 g q.d.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cefotaxime</td>
<td>50 mg/kg t.i.d. (1–18 years of age) 2 g q.d.</td>
<td></td>
</tr>
<tr>
<td>Burkholderia cepacia complex</td>
<td>Ceftazidime</td>
<td>50 mg/kg t.i.d. (1–18 years of age) 2–3 g t.i.d.</td>
<td>A combination of at least two antibiotics from different classes should be used</td>
</tr>
<tr>
<td></td>
<td>Meropenem</td>
<td>25–40 mg/kg t.i.d. (4–18 years of age) 2 g t.i.d.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Imipenem</td>
<td>22.5 mg/kg t.i.d. (&lt;40 kg) 1 g t.i.d.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piperacillin–tazobactam</td>
<td>90 mg/kg q.d. (children) 4.5 g q.d.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trimethoprim–sulfamethoxazole</td>
<td>240 mg b.i.d. (6 months to 6 years of age) 480 mg b.i.d. (6–12 years of age) 960 mg b.i.d. (&gt;12 years of age)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tobramycin†</td>
<td>10 mg/kg daily</td>
<td>Plasma concentration monitoring required</td>
</tr>
<tr>
<td>Stenotrophomonas maltophilia</td>
<td>Ticarcillin–clavulanate</td>
<td>80–100 mg/kg q.d. (&lt;18 years) 3.1 g q.d.</td>
<td></td>
</tr>
</tbody>
</table>

This table is intended as a guide only, antibiotic choice may vary dependent on local resistance profiles and antibiotic availability.

†Therapeutic drug monitoring is required.

Avoid tetracyclines in patients under 12 years of age.

b.i.d.: Twice daily; Max: Maximum dose; q.d.: Four-times daily; t.i.d.: Three-times daily.

Data taken from the Report of the UK Cystic Fibrosis Trust Antibiotic Working Group, and the Australian Therapeutic Guidelines [82,83].
with high rates of allergy [115]. Carbapenams (meropenem and imipenem) and fourth generation cephalosporins (cefeplime) display activity against both Gram-positive and Gram-negative bacteria, suggesting they may have utility in treatment of co-infection with *S. aureus* and *P. aeruginosa* [116]. Meropenem has demonstrated equivalence to ceftazadime containing regimes in treating pulmonary exacerbations, with lower rates of *P. aeruginosa* resistance developing [117, 118]. However, the recent emergence in CF of *P. aeruginosa* mutants producing metal-β-lactamases capable of inactivating all clinical β-lactam substrates (with the exception of aztreonam) raises concerns that increasing resistance rates will be seen in the future [119]. Meropenem also has high *in vitro* activity against anaerobic bacteria present in the CF airway secretions, suggesting it may have additional benefits compared to other antipseudomonal agents in the setting of polymicrobial infection [52]. There are no comparative trials of the cefepime to other treatment regimes in CF, and higher rates of *in vitro* *P. aeruginosa* resistance have been reported in comparison to ceftazidime [120]. The monobactam antibiotic, aztreonam, has a spectrum of activity limited to Gram-negative organisms. Aztreonam

### Table 4. Currently licensed antibiotics for the treatment of *Pseudomonas aeruginosa* in cystic fibrosis.

<table>
<thead>
<tr>
<th>Class</th>
<th>Drug</th>
<th>Route of administration</th>
<th>Dose</th>
<th>Special considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>β-lactams</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extended spectrum penicillins</td>
<td>Ticarcillin/clavulanate†</td>
<td>Intravenous</td>
<td>80–100 mg/kg q.d. (child) 3.1 g q.d. (adult)</td>
<td>Need to be administered by slow intravenous infusion</td>
</tr>
<tr>
<td></td>
<td>Piperacillin/tazobactam†</td>
<td>Intravenous</td>
<td>90 mg/kg q.d. (child) 4.5 g q.d. (adult)</td>
<td></td>
</tr>
<tr>
<td>Third generation cephalosporin</td>
<td>Ceftazidime</td>
<td>Intravenous</td>
<td>50 mg/kg t.i.d. (under 18 years) 3 g t.i.d. (adult)</td>
<td></td>
</tr>
<tr>
<td>Carbapenems</td>
<td>Meropenem†</td>
<td>Intravenous</td>
<td>25–40 mg/kg t.i.d. (4–18 years old) 2 g t.i.d. (adult)</td>
<td>Need to be administered by slow intravenous infusion</td>
</tr>
<tr>
<td></td>
<td>Imipenem†</td>
<td>Intravenous</td>
<td>22.5 mg/kg q.d. (under 40 kg) 1 g t.i.d. (over 40 kg)</td>
<td></td>
</tr>
<tr>
<td>Monobactam</td>
<td>Aztreonam</td>
<td>Intravenous</td>
<td>30 mg/kg (under 2 years) 50 mg/kg (2–12 years) 2 g t.i.d. (over 12 years)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inhaled‡ 75 mg t.i.d.</td>
<td>US FDA approved</td>
</tr>
<tr>
<td>Fourth generation cephalosporin</td>
<td>Cefepime</td>
<td>Intravenous</td>
<td>50 mg/kg b.i.d. (under 40 kg) 2 g b.i.d. (over 40 kg)</td>
<td></td>
</tr>
<tr>
<td><strong>Aminoglycosides</strong></td>
<td>Tobramycin</td>
<td>Intravenous</td>
<td>10 mg/kg daily§</td>
<td>Plasma concentration monitoring required</td>
</tr>
<tr>
<td></td>
<td>Tobramycin inhalation solution</td>
<td>Inhaled‡</td>
<td>300 mg b.i.d.</td>
<td></td>
</tr>
<tr>
<td><strong>Fluoroquinolones</strong></td>
<td>Ciprofloxacin</td>
<td>Oral</td>
<td>15 mg/kg (under 5 years) 20 mg/kg (5–18 years) 750 mg b.i.d. (adult)</td>
<td>Mild exacerbations and eradication regimens</td>
</tr>
<tr>
<td><strong>Polymyxin B</strong></td>
<td>Colistin</td>
<td>Intravenous</td>
<td>25000 units/kg t.i.d. (under 60 kg) 2 million units t.i.d. (over 60 kg)</td>
<td>Need to be administered by slow intravenous infusion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inhaled‡ 1 million units b.i.d. (under 2 years) 2 million units b.i.d. (over 2 years)</td>
<td></td>
</tr>
<tr>
<td><strong>Other agents</strong></td>
<td>Fosfomycin</td>
<td>Intravenous</td>
<td>100 mg/kg (under 40 kg) 5 g t.i.d. (over 40 kg)</td>
<td></td>
</tr>
</tbody>
</table>

†Co-administration of probenecid may be considered to increase drug levels.

‡Have not been studied in treatment of exacerbations.

§Therapeutic drug monitoring is required.

b.i.d.: Twice daily; q.d.: Four-times daily; t.i.d.: Three-times daily.
contains an unfused β-lactam ring that confers low cross-reactivity with other β-lactam drugs meaning that it can be used safely in patient with penicillin hypersensitivity [121].

Colistimethate sodium (colistin) was originally discovered in the 1940s, but seldom used for several decades due to concerns about its adverse effects. However, it has re-emerged as an antibiotic in patients with CF due to its activity against Gram-negative bacteria including multidrug resistant P. aeruginosa. The major adverse effects limiting its use are nephro- and neuro-toxicity [122]. Parenterally administered colistin may be most suited for patients with multidrug resistant P. aeruginosa, or in patients where aminoglycosides are contraindicated due to previous toxicity.

Fosfomycin is another ‘forgotten’ drug with efficacy against multidrug resistant P. aeruginosa. Despite evidence for its clinical efficacy in CF being limited to cohort and case studies only [123], in vitro data demonstrating its ability to penetrate biofilms, and to act synergistically with agents from each of the major classes of antipseudomonal antibiotics [124], combined with a benign side effect profile suggest it is a useful second-line agent [125]. However, potential for resistance to develop suggests its use is best used only in patients with limited antibiotic options due to allergies and toxicity of other antibiotic agents [126].

Where, how & which antibiotic?
During a severe pulmonary exacerbation, a patient’s clinical status should dictate the need for hospital admission. However, many patients with milder exacerbations prefer home-based treatment, which reduces the impact on work and family commitments [127]. When comparing home with hospital treatment the available small studies present conflicting evidence. The equivalent outcomes and improved quality of life from home-based treatment demonstrated in some studies [127,128] needs to be considered in the context of other studies that have demonstrated greater improvements in lung function and weight with hospital-based treatment, as well as a reduction in the duration of therapy [129,130]. A recent, large (>1500 patients) retrospective study has supported home-based treatment demonstrating that although hospital-treated patients appear to gain greater improvement in lung function in the immediate post-treatment period, long-term outcomes, and time to next exacerbation were similar regardless of treatment location [131].

Once treatment location is decided the next consideration is how to administer therapy. As discussed previously, fluoroquinolones are the only orally administered bioavailable antipseudomonal agents. Ciprofloxacin is the most commonly prescribed quinolone, and is frequently combined with a nebulized agent in outpatient treatment regimens for mild exacerbations. Nebulization allows delivery of high drug concentration directly to the airway whilst avoiding systemic adverse effects. Unfortunately inhaled administration of antibiotics fails to treat recalcitrant bacteria sequestered in under-ventilated lung regions. Until recently aminoglycosides and colistin were the only nebulized agents in clinical use. However, multicenter Phase III randomized controlled trials (RCTs) have recently demonstrated the safety and efficacy of aerosolized aztreonam lysine in stable patients with moderate-to-severe lung function impairment [132,133], which has supported US FDA approval for use as a maintenance treatment in CF.

Despite oral and nebulized combination regimes often being used in clinical practice, there is limited evidence to support their use in the acute setting. A Cochrane review identified three small randomized controlled trials comparing ciprofloxacin monotherapy with combination intravenous therapy. No major differences in outcome were seen, but each of the trials was under-powered and the treatment arms were not blinded [134].

Intravenous antibiotic regimes remain the cornerstone of treatment of severe exacerbations in hospitalized patients. Intravenous therapy may also be delivered effectively in the home, providing patients have reliable intravenous access, are appropriately educated in self-administration and have access to 24 h medical support should difficulties arise.

Further considerations when administering intravenous antibiotics-in-the-home setting include the mode of delivery (infusion vs slow intravenous injection) and the stability of the agents in solution. A number of antibiotics demonstrate limited stability in solution (e.g., meropenem) and the patient must be educated in the sterile preparation of these prior to each administration. To overcome the obstacle of slow intravenous infusion of medication a number of small, portable pressure driven devices have been designed, which deliver a fixed rate of drug delivery and negate the inconvenience of infusion pumps and gravity driven delivery.

The superiority of combination intravenous therapy for Gram-negative nosocomial
pneumonia has been clearly demonstrated [135]. However, in the setting of chronic pulmonary infection in CF, systematic reviews comparing combination with monotherapy have failed to clearly demonstrate superiority of combination therapy [134,136,137]. However, whilst acknowledging the current lack of evidence, treatment guidelines recommend dual antipseudomonal antibiotic therapy [82,137]. No combination regimen has demonstrated clear superiority over the others, but in practice two agents from different antimicrobial classes (usually a β-lactam and aminoglycoside) are typically administered.

In selecting specific agents current practice guidelines recommend reference be made to available sensitivity profiles, and also recommend avoiding agents to which organisms are resistant [82]. However given the previously discussed limitations of routine sensitivity testing, and their poor correlation with clinical response, an alternate approach is to select antibiotics to which the individual patient has previously responded. Anecdotally, clinicians may only refer to antibiotic sensitivity profiles when second-line agents are being selected, in the situation where the patient has failed to improve with initial treatment regimen.

Finally, lifetime cumulative exposure to antibiotics results in rates of β-lactam allergy of up to three-times that of the general population, which limits treatment options in a significant proportion of patients. In work from our group, Burrows et al. demonstrated a prevalence of 36% for allergy to a single class of β-lactam antibiotic, and 19% of patients had multiple β-lactam allergies [115]. In some patients with multiple antibiotic allergies hospital-based desensitization protocols allow the safe re-introduction of β-lactams to which they have previously reacted [138]. However, recurrent allergy is common and patients must be closely monitored. The additional burden is that desensitization must be repeated for each individual treatment course.

Duration of therapy

There are no RCTs studying the optimum duration of antibiotic therapy for pulmonary exacerbations in CF [137,139]. Theoretical concerns that a shorter duration of antibiotic therapy may reduce the time to the next exacerbation, or increase the rate of lung function decline, need to be balanced against the potential adverse effects [2], and risk of promoting antibiotic-resistant organisms [4], which may be associated with prolonged treatment courses.

Prospective studies in the treatment of acute exacerbations of chronic bronchitis, and microbiologically proven ventilator-associated pneumonia (VAP) have demonstrated noninferiority of shorter courses of antibiotics [140,141]. Although, of note in the case of VAP, patients infected with Gram-negative organisms (commonly P. aeruginosa) had an increased risk of microbiological relapse with shorter treatment [144].

In a small prospective cohort study of 22 CF patients undergoing hospital-based treatment for pulmonary exacerbations, improvements in spirometry and oxygenation plateaued after 8 days of therapy [142]. These limited prospective data are supported by a recent large retrospective study of outcomes following pulmonary exacerbations in over 1500 people, which suggested that further improvements in spirometry after 8–10 days of therapy were small, and that shortening antibiotic duration did not adversely affect the time to next exacerbation. Adequately powered prospective studies are required to more fully understand the optimal duration of treatment for pulmonary exacerbations in CF [131].

New antipseudomonal antibiotic options
Development of new antibiotic agents over the past two decades has been limited. Factors that contribute to the reluctance of pharmaceutical companies to invest in antibiotic development include microbiological (e.g., bacterial adaptability leading to resistance while drugs are still in development), regulatory (e.g., need to demonstrate superiority to other agents prior to licensing) and financial (greater profitability in development of other pharmaceuticals e.g., anticancer or immunomodulatory agents) [143,144]. Therefore, recent developments have instead focused on repackaging existing agents, for example for inhalation delivery. Alongside the recently licensed inhaled aztreonam, other inhalational preparation undergoing investigation in RCTs (both Phase II and III) include levofloxacin, coformulation of fosfomycin and tobramycin, liposomal amikacin, and dry powder formulations of tobramycin, colistin and ciprofloxacin [145,146]. Although these medications are being developed primarily for use in maintenance regimens they have the potential to be studied for use in the treatment of pulmonary exacerbations.

Novel targets for drug development

The formation of a biofilm that offers physical protection to P. aeruginosa from host immune clearance and antimicrobial agents represents a
significant challenge to developers of new anti-

A novel approach has been to conjugate antibi-

Quorum sensing is essential to the develop-

Biofilm 'dispersal' is a naturally occurring

Iron is an essential nutrient to

The studies discussed above offer exciting

Future perspective

Adjunctive therapies to prevent & treat pulmonary exacerbations

The proven benefits of oral corticosteroids in

Iron is an essential nutrient to

Iron is an essential nutrient to

Iron is an essential nutrient to

Iron is an essential nutrient to

Iron is an essential nutrient to

Iron is an essential nutrient to

Iron is an essential nutrient to

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Iron is an essential nutrient to

Iron is an essential nutrient to
Given the significant deleterious effects and increased healthcare costs associated with pulmonary exacerbations effective utilization of maintenance treatments to prevent their occurrence is paramount [158]. Much of the improvement seen in the health of people with CF has coincided with the development of multidisciplinary CF care teams, and wherever feasible patient care should be coordinated by a CF specialist center [159,160].

Maintenance exercise and physiotherapy regimens are vital in assisting clearance of viscous airway secretions. A number of chest physiotherapy techniques, including active cycle of breathing, percussion and autogenic drainage, as well as a range of hand-held expiratory oscillatory devices are available to enhance airway clearance, but superiority of one method over the others has not been established, and the individual method employed is usually negotiated between the patient and the expert physiotherapist [161]. Despite widespread acknowledgment of the importance of physiotherapy in maintaining lung health in CF, there are few studies that report on the impact on prevention of, and recovery from pulmonary exacerbations [158].

Inhaled mucolytic and rehydrating agents including recombinant DNase (Dornase alfa), hypertonic saline and mannitol further facilitate sputum clearance, and have an established role in maintenance regimens [162–164]. Although the role of these agents in the treatment of exacerbations has not been established, pulmonary exacerbations are typically accompanied by an increase in volume and purulence of respiratory secretions, and clearance of these secretions is important in resolution of exacerbations. Therefore maintenance mucolytic regimens should be continued and where tolerated, intensified during exacerbations [137]. However, in clinical practice, tolerance of hypertonic saline and mannitol may be reduced during periods of heightened airway inflammation, especially in patients with severe lung disease.

The use continuous or cyclical courses of antibiotics have been extensively investigated as a method of preventing lung function decline. CF specialist centers in Denmark attribute increased survival in their patients to administration of regular parenteral antibiotics, irrespective of clinical status [165]. However, clinical trials have yet to show superiority of this approach over prescribing antibiotics based on symptoms [114,166]. An alternate approach is to use regular inhaled antibiotics either continuously or on alternate months. This approach was subject to a recent Cochrane review that identified 17 RCTs comparing maintenance inhaled antibiotic regimens to placebo. The review concluded that inhaled antibiotic use was associated with improved lung function, and a reduction in exacerbation rates, but increased rates of resistant P. aeruginosa were observed in the antibiotic treated patients [167]. Oral maintenance anti-staphylococcal treatment has been widely prescribed in young children in an attempt to prevent S. aureus infection and lung damage. Such regimens reduce rates of S. aureus isolation but beneficial effects on lung function or exacerbation rates have not yet been seen, and concern exists that these regimens may result in increased rates of P. aeruginosa acquisition [168]. Use of oral azithromycin has been shown to improve lung function and reduce exacerbations rates, particularly in patients with chronic P. aeruginosa infection and should be continued during pulmonary exacerbations [15,169,170].

Noninvasive ventilation (NIV) is an emerging therapy in CF [171], which may be used as a physiotherapy adjunct, or as a means of short-term ventilatory support. The need for invasive mechanical ventilation (IMV) during a pulmonary exacerbation is associated with poor survival, and IMV is a contraindication to acute lung transplantation in many centers [43]. NIV has been proposed as an adjunct to prevent the need for IMV. Although there are no RCTs comparing NIV to IMV in CF, observational studies suggest NIV treatment is associated with better outcomes during pulmonary exacerbations and can be used as a bridge to lung transplantation in patients with chronic respiratory failure [44,172–174]. These studies are likely subject to selection bias, but do support a trial of NIV in exacerbations complicated by respiratory failure. As an adjunct to physiotherapy, NIV has been shown to reduce hypoxia and improve tolerance of treatment [175].

Malnutrition is common in CF, and results in reduced lung function and survival [5,176]. Improving nutritional status using high-energy/high-protein supplements may prevent deterioration in lung function [177,178]. However, addressing dietary issues is often difficult and requires expert dietetic, nursing and psychological input in order to not only institute nutritional supplements, but also engender the behavioral changes required to maintain modifications over a prolonged period. The challenge of maintaining weight is added to by a further worsening of the already increased resting energy expenditure present in CF [142], which is often accompanied by a decrease in appetite and anorexia, as well as nausea related to antibiotics. In this setting, although oral supplements
are typically used in the first instance, enteral feeding may also need to be considered [179].

**Conclusion**

Despite the recognized importance of pulmonary exacerbations in lung function decline and reduced survival in CF, much is still unknown about their etiology, and treatment is still largely based on expert opinion and experience.

**Future perspective**

It is hoped that the emergence of molecular techniques capable of more accurately representing the bacterial diversity within respiratory secretions, a greater understanding of the biofilm model of bacterial communities, and the development of techniques to test antibacterial agents in *in vitro* models that mimic more closely conditions in the CF airways will herald advances in the treatment of exacerbations.

The polymicrobial nature of infection adds to the complexity in decision making in the treatment of pulmonary exacerbations and will make studies of antibiotic effectiveness more complex, and harder to interpret. In the absence of new classes of antibiotics, novel approaches to airway infection in CF will be required to ensure ongoing improvements in the health of people with CF.

**Executive summary**

- Acute pulmonary exacerbations contribute to diminished quality of life, reduced lung function, morbidity and mortality in cystic fibrosis (CF), and remain a major obstacle to further improving survival.

**Definition**

- The lack of a universally accepted definition of a pulmonary exacerbation prevents direct comparisons being made between clinical trials.
- Future directions:
  - Identification of biomarkers reflective of clinical status may facilitate the creation of a standard definition for application in research and clinical practice.

**Epidemiology**

- Risk factors for pulmonary exacerbations include previous exacerbations, reduced lung function, female sex, and chronic *Pseudomonas aeruginosa* infection.
- Future directions:
  - Monitoring the changes in the epidemiology of airway infection, including emerging bacterial pathogens patterns will be crucial in monitoring response to new therapeutic strategies.

**Etiology**

- Acute exacerbations occur when the balance between chronic bacterial infection and host immunity is perturbed. Some exacerbations are triggered by acute bacterial or viral infections, but in many cases the cause is unknown.
- Future directions:
  - Identification of common pathways by which infectious and noninfectious stimuli trigger acute exacerbations may allow development of novel therapeutic agents.

**Microbiology**

- Current culture-dependent microbiological techniques are inadequate to identify the diversity of bacteria present in the CF airway, and poorly predict response to treatment in polymicrobial and biofilm infections that frequently occur.
- Future directions:
  - Culture independent microbiological (metagenomic) techniques will more accurately represent bacteria present in CF airway infection.
  - Application of bioinformatic approaches to identification of bacterial resistance genes may allow more accurate prediction of treatment response.

**Treatment**

- Many aspects of treatment, including the optimum number and combination of antibiotics to use, and duration and location of treatment, are based on very limited evidence. Antibiotic options for treatment of chronic Gram-negative bacterial infections are limited, and further impacted on by development of bacterial resistance and antibiotic allergies.
- Future directions:
  - Prospective studies comparing outcomes from ‘short-course’ antibiotic regimens may allow reduction in cumulative antibiotic exposure.
  - Novel antibacterial agents will target biofilm growth and bacterial access to essential nutrients.

**Adjunctive treatment**

- Treatment in specialist centers by a multidisciplinary team including specialist nurses, physiotherapists and dieticians has significantly contributed to improved survival in CF. Adherence to maintenance therapies including physiotherapy, mucolytics and nutritional supplements are important in preventing exacerbations. Maintenance and eradication antibiotic regimens delay acquisition of chronic bacterial pathogens, but their long-term impact on outcome is as yet unknown.
- Future directions:
  - Surveillance of patients treated with *Pseudomonas aeruginosa* eradication regimens, *Staphylococcus aureus* prophylaxis, and chronic azithromycin therapy will determine the impact of these interventions on bacterial infections and long-term outcomes.
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