


REVIEW

Bacteriophage therapy for infections in CF

Benjamin K. Chan¹  | Gail Stanley² | Mrinalini Modak³ | Jon L. Koff² | Paul E. Turner^{1,4}

¹Department of Ecology and Evolutionary Biology, Yale University, New Haven, Connecticut, USA

²Department of Internal Medicine, Yale School of Medicine, New Haven, Connecticut, USA

³Department of Internal Medicine, Yale New Haven Hospital, New Haven, Connecticut, USA

⁴Program in Microbiology, Yale School of Medicine, New Haven, Connecticut, USA

Correspondence

Benjamin K. Chan, Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT 06511, USA.

Email: b.chan@yale.edu

Funding information

Project High Hopes, Grant/Award Number: PET2017

Abstract

Pseudomonas aeruginosa and *Staphylococcus aureus* are bacterial pathogens frequently associated with pulmonary complications and disease progression in cystic fibrosis (CF). However, these bacteria increasingly show resistance to antibiotics, necessitating novel management strategies. One possibility is bacteriophage (phages; bacteria-specific viruses) therapy, where lytic phages are administered to kill target bacterial pathogens. Recent publications of case reports of phage therapy to treat antibiotic-resistant lung infections in CF have garnered significant attention. These cases exemplify the renewed interest in phage therapy, an older concept that is being newly updated to include rigorous collection and analysis of patient data to assess clinical benefit, which will inform the development of clinical trials. As outcomes of these trials become public, the results will valuable gauge the potential usefulness of phage therapy to address the rise in antibiotic-resistant bacterial infections. In addition, we highlight the further need for basic research to accurately predict the different responses of target bacterial pathogens when phages are administered alone, sequentially, or as mixtures (cocktails), and whether within-cocktail interactions among phages hold consequences for the efficacy of phage therapy in patient treatment.

KEYWORDS

aerosol biology, antibiotic therapy, pneumonia, TB, viral

Extensive antibiotic use during the previous century has resulted in an alarming rise in antibiotic-resistant infections. These infections, particularly for bacterial pathogens that are resistant to multiple classes of antibiotics (also known as multidrug resistant [MDR]), significantly contribute to increased morbidity and mortality.^{1–4} As a result, treatments are increasingly reliant on drugs of last resort.^{5,6} Predictably, bacteria have now emerged that are resistant to even these drugs.^{5,6} While in some cases these bacteria may not have spread widely, the concern is warranted, and the development of new antibiotics and management strategies is urgently needed.

While antibiotic resistance increases, the antibiotic development pipeline is lagging far behind with limited evidence that novel antibiotics are being discovered and developed.⁷ Therefore, efforts by the World Health Organization have resulted in the creation of a list

of “priority pathogens” for antibiotic development, due to their public health relevance. This list contains six bacterial pathogens notable for their high levels of antibiotic resistance, as well as their ability to escape conventional therapies. These bacteria, *Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter* spp., named by the ESKAPE acronym, are becoming increasingly prevalent as MDR and pan-drug resistant (PDR) organisms that frequently escape approved treatments. For patients with cystic fibrosis (CF) and their care teams, *P. aeruginosa* and *S. aureus* are common pathogens associated with pulmonary complications and disease progression. Because of the need to frequently treat pulmonary exacerbations with antibiotics, the CF community has been wrestling with the challenges of increased antibiotic resistance for some time.

S. aureus is a Gram-positive bacterium that is highly relevant in the CF lung, where it is frequently the first bacterial pathogen cultured from those with CF.⁸ Strains with resistance to methicillin (i.e., methicillin-resistant *S. aureus* [MRSA]), have been shown to correlate with the more rapid pulmonary decline, relative to *S. aureus* strains which are sensitive to methicillin.⁹ Attempts to actively eradicate MRSA upon detection have been successful, resulting in improved forced expiratory volume 1 (FEV1) and body mass index. However, spontaneous eradication in the absence of intervention was also observed in the same study.¹⁰ Ultimately, the presence of *S. aureus* can increase the risk of subsequent *P. aeruginosa* infection by damaging lung tissue and creating an environment favorable for growth.¹¹ Thus, because *S. aureus* is one of the first identified pathogens in the lungs of those with CF that paves the way for eventual *P. aeruginosa* infection, control strategies are needed.

P. aeruginosa is a Gram-negative bacterium that thrives in myriad natural and artificial environments, which vary from household sink drains, to the natural environment (e.g., soil and water sources), and to clinics and hospitals.¹² Thus, individuals with CF readily encounter *P. aeruginosa* in their home environment and when they receive medical care. While *P. aeruginosa* is less common in pediatric CF sputum, by adulthood, the majority of patients with CF have *P. aeruginosa* in sputum, which negatively correlates with CF lung function.^{13,14} *P. aeruginosa* employs multiple strategies to colonize the CF lung, and several of these are virulence factors that induce lung inflammation and tissue damage, which may contribute to the severity of pulmonary exacerbations. While the CF community also suffers from a lack of new antibiotics, the recent development of cystic fibrosis transmembrane conductance regulator modulators may affect sputum colonization of *P. aeruginosa* and the frequency of pulmonary exacerbations.¹⁵ Although the long-term durability of these effects may be limited.¹⁶

While CF clinical outcomes and survival in the past 30 years have improved, the persistence of *S. aureus*, *P. aeruginosa*, and other Gram-negative bacteria (e.g., *Burkholderia* and *Achromobacter*), and the emergence of non-tuberculous mycobacteria that are all increasingly resistant to antibiotics, highlight the need to develop novel antimicrobial therapeutics. Ideally these will also decrease inflammation and tissue-damaging virulence factors. Such therapeutics should also have limited, if any, off-target effects, which would provide an intervention that greatly benefits patients with CF. One approach which has recently received an abundance of attention, particularly in the CF community, is phage therapy.

Bacteriophage (phage) therapy is the use of lytic phages (viruses of bacteria) to kill infectious bacteria. Such an approach harnesses phages, which are abundant in nature, to efficiently and effectively kill specific bacteria. Discovered in the early 1900s, phages have been used for human therapeutics since then, but after the discovery of penicillin, phage therapy continued in the former Soviet Union and Eastern Europe more than in Western countries. Much of the available data have been translated from Russian and suggest that over 300,000 individuals have received phage therapy over the past 100 years. While there have been few reports of adverse events,

access to the data is limited, although the general consensus is that phage therapy is safe in humans without evidence for toxicity.¹⁷⁻²⁰

Because of the emergence of MDR and PDR bacteria, phage therapy is again being seriously considered in Europe, the United States, and elsewhere as a potential approach to manage antibiotic-resistant infections. In addition to more clinical experience with phage therapy, which is summarized below, the CF Foundation has provided support to the Center for Innovative Phage Applications and Therapeutics at the University of California, and funding for phage therapy clinical trials in CF from Armata Pharmaceuticals and Yale University (J. P. Clancy, M.D., Vice President of Clinical Research, CF Foundation [personal communication, August 25, 2020]).

To date, phage therapy clinical trials have studied infectious diarrhea, wound infections, and chronic otitis media with different metrics of efficacy; however, no significant side effects have been identified. While no clinical trials have been completed in CF at this time, there are published reports of individuals with CF being treated with phage therapy before or after lung transplantation (summarized in Table 1). Kutateladze and Adamia²¹ described the treatment of pulmonary infections at the Eliava Institute of Bacteriophages, Microbiology, and Virology. This included adding phages to standard CF care. Patients with CF included both infants and adults, who received phage therapy to treat *S. aureus* and *P. aeruginosa* by nebulizer over approximately 1 week. The authors reported that phage therapy caused decreased densities of sputum bacteria, improvements in patient health, and extension of time until subsequent bacterial infection. Kvachadze et al.²² reported a case of phage therapy in a pediatric CF patient who received phage therapy to treat *S. aureus* and *P. aeruginosa* via nebulization a total of nine times once every 4-6 weeks. Phage therapy was reported to result in a reduction in bacterial titers and a 50% reduction in administered antibiotics over 9 months of treatment. While there was no change in chest imaging, both *S. aureus* and *P. aeruginosa* were undetectable after phage therapy. Subsequently, Aslam et al.²³ reported their experience with phage therapy in three postlung transplant patients. One of these patients had CF whose posttransplant course was complicated with *Burkholderia dolosa*. Phage therapy was administered with antibiotics. Initial phage therapy resulted in decreased fever and leukocytosis with evidence for improved consolidations on chest imaging. Continued therapy over approximately 6 weeks led to improved functional status. However, *B. dolosa* after 10 weeks resulted in pneumonia, sepsis, and ultimately multi-organ failure, and this patient was transitioned to hospice. Law reported the case of a 26-year-old woman with CF listed for lung transplant was treated with intravenous phage cocktail of four lytic phages every 6 h for 8 weeks in addition to antibiotics for MDR *P. aeruginosa*.²⁴ Phage therapy resulted in decreased supplemental oxygen use and reduced sputum production without evidence for recurrent exacerbation for 100 days, and this patient subsequently received a lung transplant 9 months later. Most recently, Dedrick et al.²⁵ reported the use of a phage cocktail, which included an engineered phage, to treat disseminated *Mycobacterium abscessus* in a 15-year-old individual with CF who was a postlung transplant. In this

TABLE 1 Summary of cystic fibrosis phage therapy literature

Reference	Age	Route of administration	Target bacteria	Outcome
[21]	Pediatrics and adults	Inhaled	<i>Pseudomonas aeruginosa</i> <i>Staphylococcus aureus</i>	Reduced sputum bacteria density; clinical improvement; and extended time to recurrence of infection
[22]	Pediatric	Inhaled	<i>P. aeruginosa</i> <i>S. aureus</i>	Reduced sputum bacteria density; reduction of administered antibiotics over 9 months
[23]	Adults Pretransplant Posttransplant	Intravenous	<i>P. aeruginosa</i> <i>Burkholderia dolosa</i>	Improved chest imaging and clinical improvement
[24]	Adult	Intravenous	<i>P. aeruginosa</i>	Decreased supplemental oxygen, reduced sputum production
[25]	Pediatric	Intravenous	<i>Mycobacterium abscessus</i>	Decreased lesions; increased lung and liver function; improved chest imaging; and weight gain

case, phage therapy resulted in decreased size of skin lesions, and improvement in lung function, liver function, chest imaging, and weight gain. The above cases have focused on CF patients with acute clinical issues, or continued clinical decline in the setting of MDR bacteria. We have successfully treated multiple CF-associated infections at Yale-New Haven Hospital and phage therapy is associated with a rapid decrease in sputum bacteria density that correlates with short-term improvement in FEV1 for some individuals (data unpublished). This approach focused on clinically stable outpatient CF subjects with MDR or PDR bacteria that contributed to the clinical decline. This experience and those of others have been invaluable as we and others proceed with clinical trials.

The use of phage therapy will also be affected by our improved understanding of the CF microbiome. It is obvious that the CF microbiome changes with age, disease severity, and in response to antibiotic treatment, and our understanding of these changes have improved dramatically²⁶. Briefly, in the CF airways, a diverse microbiome is present early in life. However, disease progression, combined with increased antibiotic exposure, leads to changes in the CF microbiome. This coincides with an increased prevalence of *Staphylococcus* in childhood that changes to *P. aeruginosa*, which is the predominant sputum pathogen in CF adults. As noted previously, *P. aeruginosa* uses an array of virulence factors to develop resistance, and this also occurs with other Gram-negative bacteria. Therefore, phage therapy may have a role in treating such MDR and PDR pathogens. However, such cases may be dependent on identifying and characterizing effective phage(s). The addition of phage therapy to antibiotics to treat pulmonary exacerbations may provide increased efficacy and decreased duration of chemical antibiotic treatments. In addition, there may be a role for phage therapy to treat CF sputum bacteria outside of pulmonary exacerbations. One could envision such approaches may use phage therapy as an antibiotic-independent approach to modify CF airway bacteria. Examples of this may include phage therapy as an adjunct to strategies to eradicate first acquisition of *P. aeruginosa*, or potentially independent of

antibiotics, and to provide additional inhaled options to treat *P. aeruginosa* or *Staphylococcus*. These approaches will need to be rigorously studied to ensure that phage therapy does not alter the CF microbiome negatively in clinically stable patients. However, given the potentially selective, intrinsic narrow-spectrum nature of phage therapy compared to antibiotics, such approaches seem worthy of investigation.

While the existing published literature in CF is limited, there are encouraging signs that phage therapy may provide clinical benefit, which needs to be confirmed in rigorous, double-blinded, randomized-controlled clinical trials. In addition, these cases highlight potential differences in route of phage administration (e.g., intravenous vs. inhaled), concomitant use of antibiotics, short-term or longer term duration of therapy, choice of phage, and single-phage versus multiphage “cocktails.” These differences could have a major impact on outcomes, and through studies propelled by recent interest, the specific contribution of each approach can be identified.

Above, we discuss how the resurged interest in phage therapy and promising outcomes from administered treatment in human patients highlight the need for abundant basic and applied research. Here, we highlight two examples that pertain to (i) effects of differing strategies for administering phages and whether these would cause problems in accurately predicting how to target bacteria will evolutionarily respond, and (ii) cocktail approaches to phage therapy and how the supposed benefits of cocktails for covering “genotype space” of target bacterial strains might be offset by the costs of phage–phage interactions that diminish cocktail efficacy.

Recently, Wright et al.²⁷ examined the evolution of bacterial resistance to phages, by studying interactions between *P. aeruginosa* strain PAO1 and phages that bind to host cells by utilizing either lipopolysaccharide (LPS) or the type-IV pilus. In particular, they assessed whether sequential exposure to the two different phages caused mutational evolution of phage resistance in the target bacterial population that was distinct from resistance evolution when the two phages were placed together in a cocktail (mixture). This

possible differing outcome relates to the general idea that biological evolution, in response to selection by a single environmental challenge (each phage alone), may differ from molecular evolution in response to the same environmental challenges when experienced simultaneously (phage mixture) (e.g., see Kassen²⁸ on evolution in simple vs. complex environments). Results showed that the genetic basis of bacterial resistance in response to sequential phage exposure generally led to mutations in genes associated with the binding target (LPS or type-IV pilus), indicating the evolution of additive resistance in the target bacterial populations. Whereas this accumulation of multiple receptor-specific resistance mutations was never observed when phage pairs targeting different binding sites were applied simultaneously. Rather, half of the observed phage-cocktail-resistant mutants showed only LPS changes and no detected mutations in genes for the type-IV pilus; the remaining mutants either surprisingly presented no mutational changes or showed duplications in genes for bacterial recombination that could not easily explain their supposed relationship to evolved phage resistance. In this study, the data indicated that bacterial evolution in response to sequential phage exposure was both more predictable and interpretable, relative to bacterial evolution against the same phages when mixed together as a cocktail.²⁷ In turn, because phage-steering approaches are designed to leverage phage killing of target bacteria alongside predictable clinically-useful evolution of resistance trade-offs in bacterial pathogens,^{29,30} the study by Wright et al.²⁷ suggests that administering phage cocktails can cause the accuracies of these predictions to break down.

If bacteria evolve resistance to phage attack, this phenotypic change may be costly, such as incurring a reduced growth ability in phage-resistant mutants. Such pleiotropic costs of phage resistance should be commonplace, owing to the tendency for phages to evolve specific binding to highly conserved structures on host cells^{31,32}; altering (or deleting) these binding targets should, therefore, debilitate bacterial growth. By this logic, simultaneous evolution of cross-resistance to phages that bind to different cellular targets may be more costly for host bacteria, due to evolutionary constraints (i.e., cross-resistance should be unlikely when phages bind differently) combined with the expectation that distinct resistance mutations for each phage will cause fitness to decrease additively or negatively synergistically. Clearly, the evolution of high-cost resistance in target bacteria would be advantageous for phage therapy applications, because this outcome should improve the goal of reducing bacterial load. However, there is mixed evidence for the prediction that simultaneous evolution of resistance to multiphage cocktails should be more costly for bacteria, relative to fitness costs associated with sequential phage application. Wright et al.²⁷ observed that sequential resistance was more costly than simultaneous resistance in half of their replicates. Similarly, in a separate study involving additional phage pairs and *P. aeruginosa* strain PAO1, *in vitro* data showed no differences between sequential and simultaneous phage exposure, in terms of bacterial clearance or cost of resistance.³³ Again, the equivocal results for phenotypic costs of resistance against sequential versus simultaneous phages in these studies suggest that

cocktails are not necessarily the best therapeutic option; the resulting resistant bacteria may be equally debilitated in growth, whereas only sequentially administered phages tend to cause predictable underlying genetic changes in resistant mutants.²⁷

Although phage cocktails are popularly touted in the literature, it is known that the temporal dynamics of multiphage therapy can be complicated.³⁴ As an example, phages may be mixed together in equimolar amounts and applied simultaneously, but (as with any biological entities) there is no guarantee that the phages will be equivalent in their rates of cell entry, intracellular rates of genome replication and packaging, lysis timings, and burst sizes. These different characteristics would easily cause the phage cocktail to deviate from the intended equal representation of virus types in the mixture as phage particles interact with host cells during therapy, resulting in different relative killing abilities and selection pressures exerted on the bacteria. In theory, any concerns over this possible imbalance could be eliminated if the phages in the cocktail were chosen specifically because they were equal in the various phage traits. However, this notion seems unrealistic, given that even single mutations can radically alter traits of phages that are otherwise isogenic.^{35,36} Moreover, this strategy would likely undermine the generally popular goal of discovering and combining functionally distinct phages into a single cocktail based solely on their different host range (e.g., cell-binding) properties. Aside from differing growth capabilities of phages that can alter the intended equal representation of phages in an administered cocktail, effects of phage–phage intracellular competition can complicate predictions of phage-therapy efficacy. The multiplicity of infection (MOI) is defined as the ratio of phage particles to susceptible bacterial cells when these microbes are combined. MOI is easily controlled in laboratory experiments with phage and bacteria, because it is trivial to accurately measure particle titers and cell densities to achieve the intended initial ratios.³⁷ However, MOI cannot be controlled *in vivo*; phage titer is known upon delivery, but the exact size of the infecting bacterial population is very difficult to ascertain. This becomes important because elevated MOIs (i.e., ratios exceeding 1.0) allow higher probabilities that multiple phage particles coinfect the same host cell, producing phage–phage competition that can select for virus traits that foster antagonistic interactions between viruses.^{38–41} An extreme example is the evolution of “cheating” where phages are selected to selfishly utilize proteins coded by other coinfecting viruses, causing both wildtype and non-cheater variants of viruses to be competitively disadvantaged for intracellular growth.^{38,42} The net result is for cheater variants to take over the phage population, which surprisingly can occur even if there is a high phenotypic cost of cheating in the phage. For the latter reason, phage–phage competition can both reduce the variability of the overall phage community, as well as decrease the efficacy of phage particle production if phage competitiveness does not correlate with an advantage in burst size.⁴⁰ Obviously, the concern over adverse phage–phage interactions become minimized if phages are used alone or sequentially, relative to the complexities that might occur when cocktails are employed. Nevertheless, we note that these and

other possible negative consequences of the phage–phage competition remain poorly studied in phage therapy, making it currently difficult to predict how different treatment strategies would be affected by the phenomenon.

As planned trials are initiated and completed, the outcomes should allow us to determine the impact of phage therapy on pulmonary infections associated with CF. Individual cases treated by our group and others have suggested a clinical benefit from the use of phage therapy in complicated cases, but until we have data from randomized-controlled clinical trials, we can only speculate. Such clinical research will need to assess the treatment of pulmonary exacerbations and chronic sputum pathogens. In addition, potential differences in route of phage administration (e.g., intravenous vs. inhaled), concomitant use of antibiotics, short-term or longer term duration of therapy, choice of phage, and single-phage versus multiphage “cocktails” will need to be studied. At the same time, additional efforts will need to be made to expand existing phage libraries to obtain phages to treat MDR and PDR pathogens.

AUTHOR CONTRIBUTIONS

Benjamin K. Chan, Gail Stanley, Mrinalini Modak, Jon L. Koff, and Paul E. Turner reviewed the literature and wrote the manuscript.

ORCID

Benjamin K. Chan  <https://orcid.org/0000-0002-1783-2749>

REFERENCES

- Maragakakis LL, Perencevich EN, Cosgrove SE. Clinical and economic burden of antimicrobial resistance. *Expert Rev Anti Infect Ther.* 2008; 6(5):751-763.
- de Kraker MEA, Wolkewitz M, Davey PG, Grundmann H. Clinical impact of antimicrobial resistance in European hospitals: excess mortality and length of hospital stay related to methicillin-resistant *Staphylococcus aureus* bloodstream infections. *Antimicrob Agents Chemother.* 2011;55:1598-1605.
- de Kraker MEA, Davey PG, Grundmann H, BURDEN Study Group. Mortality and hospital stay associated with resistant *Staphylococcus aureus* and *Escherichia coli* bacteremia: estimating the burden of antibiotic resistance in Europe. *PLoS Med.* 2011;8(10):e1001104.
- Cosgrove SE. The relationship between antimicrobial resistance and patient outcomes: mortality, length of hospital stay, and health care costs. *Clin Infect Dis.* 2006;42(suppl 2):S82-S89.
- Rowland K. Totally drug-resistant TB emerges in India. *Nature.* 2012.
- Falagas ME, Karageorgopoulos DE. Pandrug resistance (PDR), extensive drug resistance (XDR), and multidrug resistance (MDR) among Gram-negative bacilli: need for international harmonization in terminology. *Clin Infect Dis.* 2008;46(7):1121-1122.
- Theuretzbacher U, Gottwalt S, Beyer P, et al. Analysis of the clinical antibacterial and antituberculosis pipeline. *Lancet Infect Dis.* 2019; 19(2):e40-e50.
- Armstrong DS, Grimwood K, Carlin J, et al. Lower airway inflammation in infants and young children with cystic fibrosis. *Am J Respir Crit Care Med.* 1997;156(4):1197-1204.
- Dasenbrook EC, Merlo CA, Diener-West M, Lechtzin N, Boyle MP. Persistent methicillin-resistant *Staphylococcus aureus* and rate of FEV1 decline in cystic fibrosis. *Am J Respir Crit Care Med.* 2008; 178(8):814-821.
- Dolce D, Neri S, Grisotto L, et al. Methicillin-resistant *Staphylococcus aureus* eradication in cystic fibrosis patients: a randomized multicenter study. *PLoS One.* 2019;14(3):e0213497.
- Cigana C, Bianconi I, Baldan R, et al. *Staphylococcus aureus* impacts *Pseudomonas aeruginosa* chronic respiratory disease in murine models. *J Infect Dis.* 2018;217(6):933-942.
- Remold SK, Brown CK, Farris JE, Hundley TC, Perpich JA, Purdy ME. Differential habitat use and niche partitioning by *Pseudomonas* species in human homes. *Microb Ecol.* 2011;62(3):505-517.
- Emerson J, Rosenfeld M, McNamara S, Ramsey B, Gibson RL. *Pseudomonas aeruginosa* and other predictors of mortality and morbidity in young children with cystic fibrosis. *Pediatr Pulmonol.* 2002;34(2):91-100.
- Nixon GM, Armstrong DS, Carzino R, et al. Clinical outcome after early *Pseudomonas aeruginosa* infection in cystic fibrosis. *J Pediatr.* 2001;138(5):699-704.
- Volkova N, Moy K, Evans J, et al. Disease progression in patients with cystic fibrosis treated with ivacaftor: data from national US and UK registries. *J Cyst Fibros.* 2020;19(1):68-79.
- Hisert KB, Heltshe SL, Pope C, et al. Restoring cystic fibrosis transmembrane conductance regulator function reduces airway bacteria and inflammation in people with cystic fibrosis and chronic lung infections. *Am J Respir Crit Care Med.* 2017;195(12):1617-1628.
- Sarker SA, McCallin S, Barretto C, et al. Oral T4-like phage cocktail application to healthy adult volunteers from Bangladesh. *Virology.* 2012;434(2):222-232.
- Bruttin A, Brussow H. Human volunteers receiving *Escherichia coli* phage T4 orally: a safety test of phage therapy. *Antimicrob Agents Chemother.* 2005;49(7):2874-2878.
- McCallin S, Alam Sarker S, Barretto C, et al. Safety analysis of a Russian phage cocktail: from metagenomic analysis to oral application in healthy human subjects. *Virology.* 2013;443(2):187-196.
- Rhoads DD, Wolcott RD, Kuskowski MA, Wolcott BM, Ward LS, Sulakvelidze A. Bacteriophage therapy of venous leg ulcers in humans: results of a phase I safety trial. *J Wound Care.* 2009;18(6):237-238.
- Kutateladze M, Adamia R. Phage therapy experience at the Eliava Institute. *Med Mal Infect.* 2008;38(8):426-430.
- Kvachadze L, Balarjishvili N, Meskhi T, et al. Evaluation of lytic activity of staphylococcal bacteriophage Sb-1 against freshly isolated clinical pathogens. *Microb Biotechnol.* 2011;4(5):643-650.
- Aslam S, Courtwright AM, Koval C, et al. Early clinical experience of bacteriophage therapy in 3 lung transplant recipients. *Am J Transplant.* 2019;19(9):2631-2639.
- Law N, Logan C, Yung G, et al. Successful adjunctive use of bacteriophage therapy for treatment of multidrug-resistant *Pseudomonas aeruginosa* infection in a cystic fibrosis patient. *Infection.* 2019; 47(4):665-668.
- Dedrick RM, Guerrero-Bustamante CA, Garlena RA, et al. Engineered bacteriophages for treatment of a patient with a disseminated drug-resistant *Mycobacterium abscessus*. *Nat Med.* 2019; 25(5):730-733.
- Huang YJ, LiPuma JJ. The microbiome in cystic fibrosis. *Clin Chest Med.* 2016;37(1):59-67.
- Wright RCT, Friman V-P, Smith MCM, Brockhurst MA. Resistance evolution against phage combinations depends on the timing and order of exposure. *mBio.* 2019;10(5):e01652-01619.
- Kassen R. The experimental evolution of specialists, generalists, and the maintenance of diversity. *J Evol Biol.* 2002;15(2):173-190.
- Chan BK, Sistrom M, Wertz JE, Kortright KE, Narayan D, Turner PE. Phage selection restores antibiotic sensitivity in MDR *Pseudomonas aeruginosa*. *Sci Rep.* 2016;6(1):26717.
- Kortright KE, Chan BK, Koff JL, Turner PE. Phage therapy: a renewed approach to combat antibiotic-resistant bacteria. *Cell Host Microbe.* 2019;25(2):219-232.

31. Smith DL, James CE, Sergeant MJ, et al. Short-tailed Stx phages exploit the conserved YaeT protein to disseminate Shiga toxin genes among enterobacteria. *J Bacteriol.* 2007;189(20):7223-7233.
32. Kortright PE, Kaitlyn E, Chan, Benjamin K, Turner. High-throughput discovery of phage receptors using transposon insertion sequencing of bacteria. *Proc Natl Acad Sci USA.* 2020;117:18670-18679.
33. Hall AR, De Vos D, Friman V-P, Pirnay J-P, Buckling A. Effects of sequential and simultaneous applications of bacteriophages on populations of *Pseudomonas aeruginosa* in vitro and in wax moth larvae. *Appl Environ Microbiol.* 2012;78(16):5646-5652.
34. Levin BR, Bull JJ. Population and evolutionary dynamics of phage therapy. *Nat Rev Microbiol.* 2004;2(2):166-173.
35. Duffy S, Burch CL, Turner PE. Evolution of host specificity drives reproductive isolation among RNA viruses. *Evolution.* 2007;61(11):2614-2622.
36. Dessau M, Goldhill D, McBride RC, McBride RL, Turner PE, Modis Y. Selective pressure causes an RNA virus to trade reproductive fitness for increased structural and thermal stability of a viral enzyme. *PLoS Genet.* 2012;8(11):e1003102.
37. Kropinski AM, Mazzocco A, Waddell TE, Lingohr E, Johnson RP. Enumeration of bacteriophages by double agar overlay plaque assay. *Methods Mol Biol.* 2009;501:69-76.
38. Turner PE, Chao L. Sex and the evolution of intrahost competition in RNA virus phi6. *Genetics.* 1998;150:523-532.
39. Turner PE. Parasitism between co-infecting bacteriophages. *Adv Ecol Res.* 2005;37:309-332.
40. Dennehy JJ, Turner PE. Reduced fecundity is the cost of cheating in RNA virus phi6. *Proc Biol Sci.* 2004;271:2275-2282.
41. Froissart R, Wilke CO, Montville R, Remold SK, Chao L, Turner PE. Co-infection weakens selection against epistatic mutations in RNA viruses. *Genetics.* 2004;168(1):9-19.
42. Díaz-Muñoz SL, Sanjuán R, West S. Sociovirology: conflict, cooperation, and communication among viruses. *Cell Host Microbe.* 2017;22(4):437-441.

How to cite this article: Chan BK, Stanley G, Modak M, Koff JL, Turner PE. Bacteriophage therapy for infections in CF. *Pediatric Pulmonology.* 2021;56:S4-S9.
<https://doi.org/10.1002/ppul.25190>