

Post-acute Sequelae of COVID-19 1



Respiratory sequelae of COVID-19: pulmonary and extrapulmonary origins, and approaches to clinical care and rehabilitation

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Although the exact prevalence of post-COVID-19 condition (also known as long COVID) is unknown, more than a third of patients with COVID-19 develop symptoms that persist for more than 3 months after SARS-CoV-2 infection. These sequelae are highly heterogeneous in nature and adversely affect multiple biological systems, although breathlessness is a frequently cited symptom. Specific pulmonary sequelae, including pulmonary fibrosis and thromboembolic disease, need careful assessment and might require particular investigations and treatments. COVID-19 outcomes in people with pre-existing respiratory conditions vary according to the nature and severity of the respiratory disease and how well it is controlled. Extrapulmonary complications such as reduced exercise tolerance and frailty might contribute to breathlessness in post-COVID-19 condition. Non-pharmacological therapeutic options, including adapted pulmonary rehabilitation programmes and physiotherapy techniques for breathing management, might help to attenuate breathlessness in people with post-COVID-19 condition. Further research is needed to understand the origins and course of respiratory symptoms and to develop effective therapeutic and rehabilitative strategies.

Introduction

Over the first 3 years of the COVID-19 pandemic, worldwide mortality among people infected with SARS-CoV-2 has reduced from a peak of 101 600 deaths per week in January 2021 to 6500 deaths per week in March 2023.¹ Similarly, hospital admissions have reduced—for example, in the UK, 36·7 per 100 000 people were admitted to hospital in January 2021, whereas 10·6 per 100 000 were admitted in March 2023.² These improvements are due in part to the availability of effective vaccines, leading to a reduction in the severity of acute illness,³ and the use of acute treatments such as dexamethasone, anti-interleukin-6 (IL-6) therapies, antivirals, and baricitinib.⁴ As with other acute respiratory viral infections that cause acute lung injury, such as SARS-CoV and MERS-CoV,^{5,6} long-term sequelae have been described after COVID-19 and are likely to increase in prevalence with increasing survivorship.

The post-acute sequelae of COVID-19 affect multiple organ systems and include a range of symptoms—among them breathlessness (dyspnoea), fatigue, and brain fog (cognitive impairment)—that persist or emerge after SARS-CoV-2 infection. These sequelae are collectively referred to as post-COVID-19 condition or long COVID (the term originally used by people with the condition), which is broadly defined internationally as the persistence of symptoms, usually for 3 months or more, and for at least 2 months, after acute SARS-CoV-2 infection that cannot be explained by an alternative diagnosis.⁷ The exact prevalence of long COVID is not known and differs according to how it is measured, the cohort being studied, the SARS-CoV-2 variant, and vaccination status. Triple vaccination against COVID-19

appears to reduce the likelihood of persistent sequelae but does not prevent the development of long COVID. In a UK survey of private households, 4·5%, 4·2%, and 5·0% of triple-vaccinated adults had persistent symptoms 12–16 weeks after confirmed SARS-CoV-2 infection with omicron BA.1, omicron BA.2, and delta variants, respectively.⁸

Risk factors for long COVID include severe acute disease (including receipt of invasive mechanical ventilation), female sex, obesity, socioeconomic deprivation, and pre-existing disease.^{9–11} These risk factors were established in high-income countries, but many are mirrored in middle-income and low-income countries where access to services might be compromised.^{12,13} Although people with poorly controlled chronic lung disease have an increased risk of severe acute COVID-19 or death,^{14,15} those in whom the pre-existing disease is well controlled do not appear to have an increased risk of severe disease, but they often have a worsening of respiratory symptoms after COVID-19. Whether worsening of symptoms in these people is due to destabilisation of the underlying chronic condition or to other COVID-19-related effects is uncertain. Potential mechanisms associated with long COVID include ongoing systemic inflammation (including activation of type I and III interferons and IL-6),¹⁶ autoimmunity, microclotting, hypoadrenalism, and viral persistence.^{17–21}

Respiratory symptoms are an important cluster of symptoms defined from a large dataset of published studies of post-acute sequelae of COVID-19.²² Respiratory symptoms (breathlessness, breathing pattern disorders such as erratic breathing and hyperventilation, and persistent cough) and underlying pulmonary disease (lung

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Key messages

- Post-COVID-19 condition (also known as long COVID) is a heterogeneous clinical syndrome that affects multiple organ systems and encompasses pulmonary sequelae and extrapulmonary disruption that can result in persistent disabling breathlessness (dyspnoea)
- The pulmonary sequelae of COVID-19 include thromboembolic disease, with thrombi and microvascular thrombi identified in the pulmonary vasculature; further work is needed to define the underlying mechanisms of chronic vascular disease after COVID-19 to inform diagnostic and therapeutic approaches
- Severe COVID-19 causes alveolar injury and induces profibrotic pathways similar to those seen in IPF, resulting in pulmonary fibrosis, particularly in individuals with genetic susceptibility; therapies that attenuate COVID-19-induced lung injury are likely to mitigate these effects, but long-term outcomes are unknown
- Individuals with well controlled pre-existing respiratory conditions, including mild-to-moderate asthma and COPD, do not appear to be at increased risk of severe COVID-19; however, people with asthma or COPD might have an increase in symptoms after COVID-19
- Extrapulmonary sequelae that might contribute to disabling dyspnoea in people with post-COVID-19 condition include physical deconditioning, and new-onset frailty or prefrailty; a range of factors, including forced inactivity, malnutrition, hypoxia, systemic inflammation, and immune-mediated damage might underlie these sequelae
- Current rehabilitation strategies to manage post-COVID-19 breathlessness have been modified from post-ICU services and chronic respiratory disease practice; common interventions include adapted pulmonary rehabilitation programmes and physiotherapy techniques

COPD=chronic obstructive pulmonary disease. ICU=intensive care unit. IPF=idiopathic pulmonary fibrosis.

fibrosis and thromboembolic disease) need to be assessed in clinical care and might require specific interventions. In this Series paper, we first describe the multisystem nature of long COVID before reviewing specific pulmonary sequelae, pre-existing respiratory conditions, and selected extrapulmonary complications that might contribute to post-acute respiratory symptoms. Finally, we consider approaches to pulmonary rehabilitation and evaluate non-pharmacological therapeutic interventions for individuals with disabling dyspnoea after COVID-19.

Post-COVID-19 condition

Breathlessness, fatigue, muscle pain, brain fog, sleep disturbance, and headache are the most prevalent symptoms reported in long COVID, independent of the severity of acute illness (defined according to whether or not hospital admission was required). In a systematic

review with an average follow-up time of 126 days, 22·6% of people who required hospital admission and 20·4% of people who did not require hospital admission reported persistent breathlessness.^{9,10,23} By contrast, cough, fever, and loss of taste (ageusia) and smell (anosmia) are highly prevalent during acute illness but are less prevalent in post-COVID-19 condition. Clustering of individual symptoms has generally not led to the identification of disease-specific clusters of symptoms, except for a potential respiratory cluster dominated by shortness of breath and chest pain.¹⁰ Nevertheless, in a meta-analysis of 54 published studies and two medical record databases,²² respiratory symptoms (dyspnoea and persistent cough) were identified as an important cluster alongside fatigue and cognitive problems. By contrast, clusters in the PHOSP-COVID (Post-hospitalisation COVID-19 study) cohort were mostly defined by the burden of symptoms and ongoing health impairments, and symptom severity was positively associated with the total number of symptoms.⁹ The more severe symptom clusters in PHOSP-COVID were also associated with lower exercise tolerance,⁹ and people in these clusters were less likely to have returned to work 6 months after hospital admission.²⁴ There were intriguing associations between obesity and ongoing systemic inflammation, with elevated blood C-reactive protein and IL-6 concentrations in the more severe clusters compared with the mild cluster, highlighting different phenotypes and potential therapeutic targets.²⁵

Although it is helpful to define a group of people who have not recovered on the basis of ongoing symptoms, we need to further understand the precise mechanisms that underlie symptoms, ongoing organ impairment, and the relationship between symptoms and organ damage and pathology. Acute lung injury is the dominant insult in severe acute COVID-19 (ie, in patients requiring hospital admission for respiratory support), in contrast to mild-to-moderate acute COVID-19 (in patients not requiring hospital admission), and any post-COVID-19 sequelae might differ between these groups, requiring specific assessments and interventions.

During the first quarter of 2020, around one in six immune-naïve patients who were admitted to hospital with COVID-19 developed severe disease requiring an intensive care unit (ICU) admission, with the majority requiring respiratory support (non-invasive or invasive mechanical ventilation).²⁶ The current risk of developing severe COVID-19 in immune-naïve patients is less clear owing to the increase in SARS-CoV-2 exposure and the difficulty of ascertaining a true immune-naïve population. Nevertheless, similar to other critical illnesses, severe COVID-19 can leave patients with long-term morbidity involving any organ system and affecting health-related quality of life and wellbeing. These consequences might be related to the underlying disease process itself or to treatments administered in the ICU to facilitate life-support therapies, or both.

For more on PHOSP-COVID see
<https://www.phosp.org/>

In PHOSP-COVID, a large, multicentre follow-up study of patients admitted to hospital with COVID-19, those who required invasive mechanical ventilation were less likely to report full recovery at 6 months after discharge than were those who required supplemental oxygen only (18·8% vs 36·3%), confirmed in analyses that adjusted for differences in patient characteristics.²⁴ In unadjusted comparisons, those requiring invasive mechanical ventilation also had lower physical performance (percentage of predicted incremental shuttle walk test distance 39·4% vs 50·1%) and worse lung physiology measured by spirometry and pulmonary diffusion capacity than did those who did not receive mechanical ventilation.²⁴ However, severity of acute COVID-19 illness was not associated with clusters representing phenotypes of patient-reported recovery, supporting the idea that some of the mechanisms that underlie post-COVID-19 condition are not directly related to acute lung injury. Furthermore, in a follow-up study of patients who were admitted to hospital with COVID-19, improvements in symptoms were noted at 2 years, but the symptom burden remained high for those who received ventilatory support in hospital compared with a control group without previous SARS-CoV-2 infection.²⁷

Most critically ill patients with COVID-19 disease develop an extensive inflammatory insult that is driven by COVID-19 pneumonitis leading to acute respiratory distress syndrome (ARDS). ARDS is an inflammatory lung injury that leads to increased vascular permeability, which can be caused by various acute insults, only one of which is viral pneumonia.²⁸ A well developed evidence base has described the sequelae of ARDS in the pre-pandemic era, which can provide insights into recovery trajectories for patients with COVID-19-associated ARDS, given the currently limited evidence base for this group of patients. Follow-up studies show that people who survive ARDS can have substantial long-term respiratory morbidity. Reports detailing pulmonary evaluation have most frequently identified mild-to-moderate reductions in pulmonary diffusion capacity at 1-year follow-up in patients with non-COVID-19-related ARDS.²⁹ Reduced exercise capacity, most commonly measured with the 6-min walk test, is evident in cohorts of patients with ARDS, improving from 60–71% of predicted distance at 12 months to 71–76% of predicted distance at 5 years after hospital discharge.³⁰

An important feature of the non-COVID-19 ARDS literature is the broader impact of post-acute sequelae on patients and their families. The consequences of critical illness extend beyond the respiratory system and might contribute to the increased incidence of physical and mental health impairments,³¹ impaired quality of life,³² socioeconomic effects as a result of not being able to work,³³ and broader effects on the family unit (eg, if family members have to adopt caregiver roles) after discharge from the ICU.³⁴ Data on long-term outcomes and the course of recovery after COVID-19 are limited; however,

in the UK (table) and elsewhere, major research funding has been allocated to understand the determinants, clinical and biological features, underlying mechanisms, and natural history of post-COVID-19 condition, to explore its wider health, social, and economic effects, and to develop strategies for management and support.

Pulmonary sequelae of COVID-19

There is growing awareness of an increased risk of thromboembolic disease and lung fibrosis in survivors of COVID-19, both of which could contribute to persistent breathlessness.³⁵ At present, insufficient evidence exists for an increased incidence of other chronic respiratory diseases after COVID-19.^{36,37} Here, we review evidence on the incidence and mechanisms of pulmonary fibrosis and thromboembolic disease after COVID-19, and discuss potential preventive and therapeutic treatment options. We also evaluate the effects of pre-existing respiratory diseases, including asthma and chronic obstructive pulmonary disease (COPD), on post-COVID-19 outcomes.

Pulmonary fibrosis

Evidence of long-term pulmonary disease following coronavirus disease in previous pandemics^{38,39} and following ARDS,⁴⁰ as well as mechanistic similarities between COVID-19-related pneumonia and idiopathic pulmonary fibrosis (IPF; figure 1),⁴¹ raise the possibility of a substantial global burden of long-term fibrosis resulting from SARS-CoV-2 infection.

Severe COVID-19 is associated with a high level of alveolar injury that can continue even after viral clearance.⁴² Such pathological changes might be caused by direct viral infection or, more commonly, by immune-mediated injury to alveolar cells,⁴³ causing a pattern of diffuse alveolar damage.^{44,45} Augmented molecular signalling from epithelial to immune cells further perpetuates tissue damage, lung injury, and disease progression.^{46,47} IPF also results from alveolar injury,⁴⁸ and shares genetic, molecular, and epidemiological risk factors with severe COVID-19 disease. Of the 19 genes known to increase the risk of IPF, several have been associated with more severe COVID-19, including *DPP9*, although *MUC5B* and *ATP11A* are associated with reduced severity.^{49,50} COVID-19 is caused by the binding of the SARS-CoV-2 virus to the ACE2 receptor. This leads to internalisation of the ACE2 receptor and, consequently, increased profibrotic angiotensin 1 and 2 signalling, as well as enhanced alveolar TGF- β signalling, which are known to stimulate fibrotic pathways such as fibronectin production, collagen synthesis, and fibroblast proliferation.^{51,52} Furthermore, high levels of collagen-secreting CTRHC1⁺ fibroblasts are associated with severe acute fibrosis and fatal outcomes in COVID-19.⁵³

The role of immune cells is also likely to be important. Raised concentrations of eosinophils, mast cells, and lymphocytes, particularly CD8⁺ cells, have been correlated with poorer lung function and increased

	Aims	Study design	Population and target n	Setting of acute COVID-19 and follow-up
Coronavirus Post-acute Long-term Effects: Constructing an Evidence Base (CONVALESCENCE; IRAS 297578)	To define long COVID, its determinants, and health, social, and economic consequences; to assess GP adherence to NICE diagnosis and management guidelines	3-year longitudinal study using data from existing population cohorts and electronic health records; a substudy will focus on deep phenotyping; part of the COVID-19 Longitudinal Health and Wellbeing National Core Study	Participants from existing studies and health records; 300–350 participants from existing population cohorts will be recruited for the deep phenotyping substudy, including those with long COVID and controls	Follow-up of hospitalised and non-hospitalised individuals
Therapies for Long COVID in non-hospitalised individuals (TLC; ISRCTN15674970)	To evaluate symptom burden and underlying pathophysiology of long COVID syndromes in adults with a previous diagnosis of COVID-19 who were not admitted to hospital, and to assess potential therapies	1-year population-based cohort study using monthly self-reported data on symptoms, quality of life, and work capability from primary care records; statistical clustering methods will be used to identify distinct long COVID symptom clusters; a substudy will focus on immune function, proteomic and genomic profiles, and physical health measures	4000 adults with past SARS-CoV-2 infection, confirmed by PCR test, and 1000 matched controls identified using GP records and the CPRD; individuals from the four most prevalent symptom clusters and two control groups will be invited to take part in the deep phenotyping substudy	Community-based cohort; self-reported data will be collected on a digital platform; substudy samples will be collected at a clinical research facility or at the participant's home
Real-time Assessment of Community Transmission Long COVID (REACT LC; IRAS 298404)	To understand the natural history and long-term sequelae of SARS-CoV-2 infection; to characterise genetic, biological, social, and environmental factors that underpin long COVID	3-year prospective longitudinal study; part of the wider REACT programme	>120 000 participants (aged ≥5 years) from REACT-1 and REACT-2 studies; 30 000 of these participants will have past SARS-CoV-2 infection confirmed on PCR or lateral flow tests; 8000 participants with past SARS-CoV-2 infection, including 4000 with long COVID, will undergo detailed clinical phenotyping investigations	Community-based cohort
The Post-hospitalisation COVID-19 study (PHOSP-COVID; ISRCTN10980107)	To understand the long-term health outcomes for patients who have been admitted to hospital with COVID-19, including detailed recording of symptoms, and physiological and biochemical testing; to investigate the effect of rehabilitation (PHOSP-R) on long COVID symptoms	Prospective longitudinal study involving 83 NHS hospitals	10 000 adults discharged from hospital after acute COVID-19; 3000 participants will undergo detailed clinical phenotyping investigations; PHOSP-R aims to recruit 132 participants with persistent symptoms >12 weeks after hospital discharge	Follow-up of hospitalised adults, including patients admitted to the ICU
Symptoms, Trajectory, Inequalities and Management: Understanding Long-COVID to Address and Transform Existing Integrated Care Pathways (STIMULATE-ICP; ISRCTN10665760)	To evaluate the effects of current interventions, including multiorgan MRI (Coverscan) and a rehabilitation app (Living with COVID Recovery), on their own and in combination with drug therapies (anticoagulant, anti-inflammatory, and antihistamine agents) on long COVID symptoms and outcomes	2-year pragmatic, cluster-randomised trial; the effect of drug therapies vs usual care will be assessed in a nested adaptive platform phase 3 trial	>4500 adults with persistent COVID-19 symptoms for >4 weeks after acute SARS-CoV-2 infection; participants will be recruited on their first visit to a long COVID clinic	Community-based cohort; follow-up assessment visits will take place at 12 and 24 weeks after the baseline visit

CPRD=Clinical Practice Research Datalink. GP=general practitioner. ICU=intensive care unit. NHS=National Health Service. NICE=National Institute for Health and Care Excellence.

Table: Summary of major funded studies investigating post-COVID-19 condition in the UK

radiological abnormalities after COVID-19.⁵⁴ Neutrophil responses are also likely to be involved in fibrosis: increased neutrophil extracellular traps (NETs) have been identified in the serum of patients in the early post-acute phase,⁵⁵ and exogenous NETs promoted fibrogenesis in epithelial cells, even though direct infection with SARS-CoV-2 did not promote fibrogenesis in an epithelial cell model.⁵⁶

Severe COVID-19 and IPF are more common in men and older individuals, and both conditions are associated with a range of comorbidities including obesity, type 2 diabetes, hypertension, and ischaemic heart disease.^{57–59} Similarly, biomarkers that have been associated with progressive IPF, such as MMP7,⁶⁰ have also been found to be elevated in people with post-COVID-19 condition who have poorer lung function.⁶¹ Notably, patients with IPF who contract COVID-19 are more likely to have poor clinical outcomes.⁶²

Organising pneumonia is the radiological pattern that is most commonly seen in COVID-19, with subsequent fibrotic remodelling occurring in some cases.^{63,64} Persistent radiological abnormalities 1 year after COVID-19 pneumonia can range from limited ground-glass opacity and subpleural reticulation to more extensive ground-glass opacity, traction bronchiectasis, and honeycombing.⁶⁵ This pattern is more prevalent among patients who are admitted to hospital, and current evidence suggests that up to 55% of these patients have persistent changes in the months following infection, although estimates vary widely.^{64,66–69} A multicentre cohort study is underway to determine the prevalence of post-COVID-19 fibrosis and to identify risk factors over a longer time span in patients admitted to hospital and in those managed in the community.⁷⁰ Preliminary analysis suggests that around 7% of patients admitted to hospital with COVID-19 will have residual lung abnormalities on

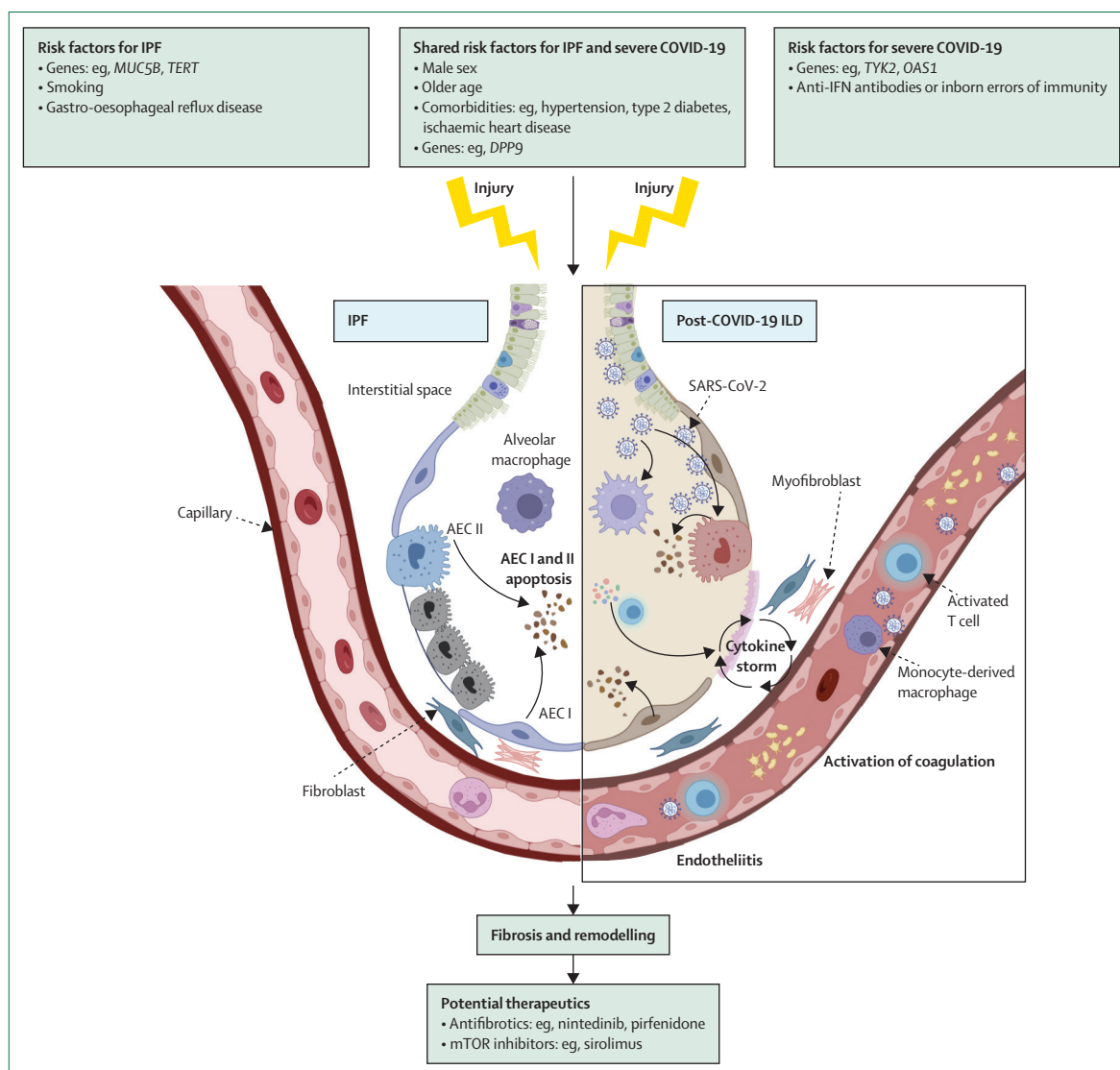


Figure 1: Shared risk factors and mechanisms in IPF and post-COVID-19 ILD

COVID-19 and IPF share several risk factors, including demographic and genetic factors and comorbidities. Furthermore, severe COVID-19 causes alveolar injury and activates profibrotic pathways similar to those observed in IPF. In IPF, resident cell populations are changed, with loss of AEC type I and development of a new subpopulation of aberrant transitional cells. In both IPF and post-COVID-19 ILD, apoptosis of AEC type I and type II occurs. In post-COVID-19 ILD, SARS-CoV-2 can directly infect AEC type II, leading to macrophage activation and recruitment of immune cells, causing sustained production of proinflammatory cytokines (ie, a cytokine storm). This proinflammatory response causes AEC and endothelial cell damage, resulting in fibroblast activation and the incorporation of collagen-rich extracellular matrix in the interstitial space. In genetically susceptible individuals, COVID-19 induction of profibrotic pathways has the potential to lead to pulmonary fibrosis. Treatments that reduce COVID-19-induced lung injury are likely to mitigate these effects, but long-term outcomes are yet to be determined. AEC=alveolar epithelial cells. *DPP9*=dipeptidyl peptidase 9. IFN=interferon. ILD=interstitial lung disease. IPF=idiopathic pulmonary fibrosis. mTOR=mammalian target of rapamycin. *MUC5B*=mucin 5B, oligomeric mucus/gel-forming. *OAS1*=2'-5'-oligoadenylate synthetase 1. *TERT*=telomerase reverse transcriptase. *TYK2*=tyrosine kinase 2. Adapted from Mehta and colleagues,⁴¹ by permission of Springer-Verlag. Figure originally created using BioRender.com.

CT within the first 12 months, with some, albeit limited, evidence of a slow resolution during the first year.³⁵ Thoracic CT changes over time following hospital admission for COVID-19 in three patients are shown in figure 2.

Considerable progress has been made in the treatment of severe COVID-19-related pneumonia, which might reduce the risk of long-term fibrosis. Most treatments that are proven to reduce COVID-19 severity target the

immune system. Corticosteroids (dexamethasone and methylprednisolone) are often used to treat organising pneumonia and ARDS,^{71,72} and have been shown to reduce mortality in severe COVID-19.^{64,73,74} Dexamethasone might limit the development of lung fibrosis by mitigating the development of severe lung injury. The mechanisms by which dexamethasone prevents lung injury are proposed to involve inhibition of neutrophil-derived type 1 interferon signalling,⁷⁵ which has been

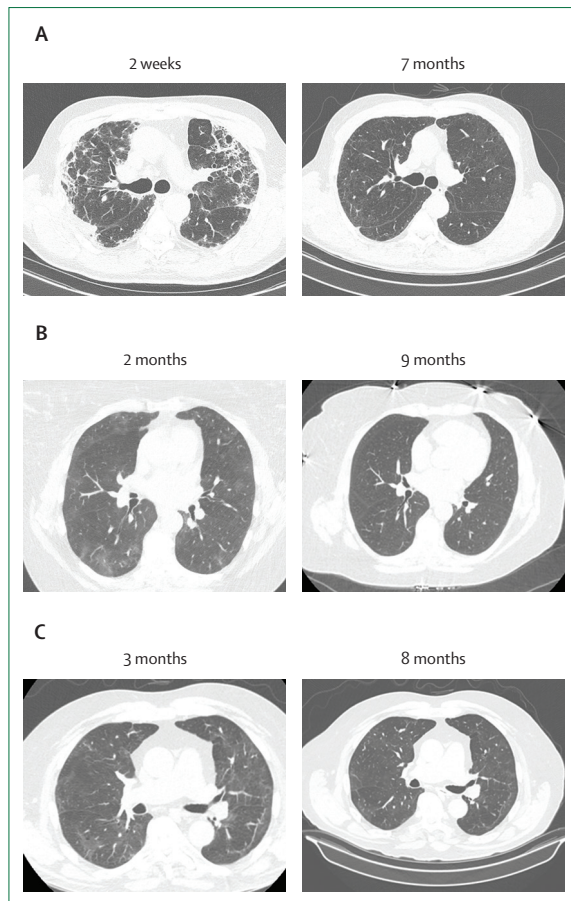


Figure 2: Thoracic CT changes following hospital admission for acute COVID-19 COVID-19 is associated with a range of changes on acute and follow-up thoracic CT scans. Thoracic CT scans shown here were acquired after discharge from three patients who had been admitted to hospital with COVID-19 (WHO Clinical Progression Scale ≥ 5). (A) CT scan from a 66-year-old man acquired 2 weeks after discharge shows initially diffuse ground-glass opacification with consolidation and interlobular septal thickening (left panel), with resolution of changes on CT imaging 7 months after discharge (right panel). (B) CT scan from a 55-year-old woman acquired 2 months after discharge shows predominantly peripheral bilateral ground-glass opacification (left panel), with resolution of changes on CT imaging 9 months after discharge (right panel). (C) CT scan from a 71-year-old man acquired 3 months after discharge shows initially diffuse ground-glass opacification and fibrosis (left panel), with partial resolution of changes and persistent fibrosis on CT imaging 8 months after discharge (right panel).

proposed to drive the development of profibrotic macrophages.⁷⁶ There are no placebo-controlled trials of steroids in post-COVID-19 interstitial lung disease (ILD), although an open-label study of high-dose (40 mg reducing to 10 mg) versus low-dose (10 mg stable dose) steroids showed that only 16 of 65 (24.6%) patients responded to the high-dose regimen, which was not significantly different from the response rate for the low-dose regimen (12 of 65 patients; 18.5%).⁷⁷ The use of steroids in COVID-19 ILD is extrapolated from the management of other inflammatory ILDs, and high bronchoalveolar lavage fluid lymphocyte counts might be a marker of corticosteroid responsiveness.^{78–80} Raised bronchoalveolar lavage fluid lymphocyte counts have

been found in 74.7% of patients with acute COVID-19 and are linked to increased disease severity.⁸¹ The timing of steroid administration might be important, with the greatest reduction in mortality seen when dexamethasone is given after the first week of illness.^{73,82,83} There is no proven benefit of administration in mild COVID-19.⁷³

Anti-IL-6 agents, such as tocilizumab and sarilumab, appear to offer a survival benefit compared with usual care in critically ill patients with severe COVID-19.^{84–86} Use of the JAK inhibitor baricitinib reduces mortality compared with usual care (with or without remdesivir and corticosteroids) and improves recovery time in patients admitted to hospital.^{87,88} Experimental models suggest that anti-IL-6 and JAK inhibition therapies might also be beneficial in IPF.^{89,90} Bioinformatic analysis has suggested that drugs with antifibrotic activity, including mTOR inhibitors and nintedanib, might be of value in treating COVID-19⁹¹ and are currently being investigated in clinical trials (NCT04948203, NCT04856111, NCT04607928, NCT04541680, and NCT04619680).

Pulmonary emboli and microvascular thrombi

The causal association between COVID-19 and acute thromboembolic disease is well established. In the acute phase, vascular endothelial dysfunction, a hyperinflammatory immune response, and a hypercoagulant state predispose patients to developing venous thromboses.⁹² COVID-19-associated coagulopathy potentially involves multiple pathways and mechanisms, including NETs, complement activation, platelet dysfunction, an imbalance of fibrinolysis, protein C, and antiphospholipid antibodies.⁹³ Remaining gaps in understanding of the pathogenesis of COVID-19-associated coagulopathy must be addressed to inform improvements in diagnostics and potential therapeutics.

The incidence of pulmonary embolism varies considerably between COVID-19 cohorts in different settings and correlates with disease severity. In patients admitted to hospital but not requiring ICU support, the incidence of pulmonary embolism is estimated to be between 0.9% and 3.4%.^{94,95} In patients admitted to the ICU, the incidence of pulmonary embolism ranges from about 8%⁹⁶ to 59% in those with severe COVID-19 requiring extracorporeal membrane oxygenation.⁹⁷ Rates in people not admitted to hospital are lower but still significant.⁹⁸ Pulmonary embolism risk continues in the non-acute stage: the pooled cumulative incidence across studies is 1.5% during short-term follow-up⁹⁹ and is still elevated at 8 weeks or more from diagnosis.¹⁰⁰

Significant risk factors for the development of venous thromboembolic complications in the context of acute COVID-19 include male sex, older age, receipt of mechanical ventilation, raised C-reactive protein, and raised D-dimer.^{101,102} The development of thromboembolic disease, in turn, is a risk factor for increased adverse outcomes, including ICU admission, mechanical ventilation, and longer median hospital admissions.¹⁰² In

the longer term, there is evidence of incomplete thrombus resolution despite anticoagulant treatment, with 30% estimated to be unresolved at 105 days.¹⁰³

In the non-pandemic setting, chronic thromboembolic pulmonary hypertension (CTEPH) is a potentially life-limiting complication of pulmonary embolism that occurs in about 4% of patients who survive an episode of acute pulmonary embolism. Despite the high numbers of patients with COVID-19-related pulmonary emboli globally, an increase in CTEPH has not been reported. A UK study of referrals to a national specialist centre did not find an increase in the incidence of CTEPH over 12 months or detect a single case that was clearly associated with COVID-19.¹⁰⁴ Given that the median lag time from index pulmonary embolism to CTEPH diagnosis has historically been 12.5 months,¹⁰⁵ it is possible that this chronic disease is yet to manifest at scale.

The apparent lack of COVID-19-related CTEPH might be due to the clot burden affecting more distal segmental anatomical locations within the pulmonary vasculature, which has been reported in several studies.^{101–103} There is evidence that subsegmental disease could represent in-situ thrombosis (immunothrombosis) due to local inflammation.^{106,107} Immunothrombosis, as opposed to thromboembolism arising from distal deep-vein thromboses, is suggested as a likely mechanism because most COVID-19-related pulmonary emboli do not present with concurrent deep-vein thromboses.¹⁰⁸ The prognostic and treatment implications of this phenotypically distinct process, compared with classic thromboembolism, are unclear. Moreover, the balance of future risk of re-thrombosis has not been defined.

Even in the absence of demonstrable CTEPH, patients might have chronic symptoms and clinically relevant biomarkers that meet the definition of persistent pulmonary embolism impairment.¹⁰⁹ This emerging syndrome has a 2-year cumulative incidence of 16% after pulmonary embolism in a non-COVID-19 context.¹¹⁰ The incidence and relevance of persistent pulmonary embolism impairment following COVID-19-related pulmonary embolism are unknown at present.

Some evidence implicates the involvement of microvascular thrombi in post-acute COVID-19 morbidity. In-situ thrombi or microthrombi are more frequently reported than are pulmonary emboli in autopsy studies.¹¹¹ Endothelial damage in the form of inflammation or necrosis are commonly reported pathological^{111,112} and electron microscopy findings in autopsy studies of patients with COVID-19.¹¹³ Alveolar gas transfer abnormalities on hyperpolarised ¹²⁹Xe MRI have been demonstrated in chronically symptomatic patients with normal CT imaging months after the acute illness.¹¹⁴ Dual-energy CT has also been used to quantify perfusion abnormalities that were not apparent on visual assessment of contrast-enhanced CT.¹¹⁵ Imaging studies have shown evidence of concurrent pathological processes including embolic disease in the macrovasculature

alongside smaller vessel disease.⁹⁷ Fibrinolysis-resistant, anomalous amyloid microclots have been identified in the plasma of patients with persistent post-COVID-19 symptoms but with normal routine coagulation profiles.¹¹⁶

There is a pressing need to clarify the extent of vascular involvement, especially in the post-acute phase of COVID-19, specifically because this could inform therapeutic options for ongoing and prospective clinical trials. Further research is also needed to define the incidence, mechanisms, diagnostics, and treatment of chronic pulmonary vascular disease following COVID-19. With regard to treatment, the HEAL-COVID trial (Helping Alleviate the Longer-term Consequences of COVID-19; NCT04801940) recently reported that 2 weeks of anticoagulant therapy with apixaban initiated at hospital discharge for COVID-19 is not an advantageous addition to the standard of care in terms of hospital re-admissions or mortality.¹¹⁷ However, the therapy in this study was prescribed to individuals with clinical equipoise and not specifically to those with an established clinical indication for anticoagulation. An active multicentre trial, STIMULATE-ICP (Symptoms, Trajectory, Inequalities and Management: Understanding Long COVID to Address and Transform Existing Integrated Care Pathways; ISRCTN10665760), which is comparing the efficacy of 12 weeks of anticoagulant, anti-inflammatory, and antihistamine therapy in post-COVID-19 condition, will provide further insight into therapeutic options in this population.

Obstructive lung disease and COVID-19

With respect to airways disease in 2020–21, many countries saw a reduction in asthma and COPD exacerbations, possibly due to reduced exposure to respiratory infections as a consequence of public health measures introduced to stop the spread of COVID-19. In people with well controlled mild-to-moderate asthma, systematic reviews have not shown an increased risk of severe COVID-19³⁷ and, overall, people with well controlled asthma are not at increased risk of COVID-19-related death.^{14,37} However, the risk of COVID-19-related death was increased in people with asthma who had recently needed oral corticosteroids for their asthma¹⁴ or had been admitted to hospital with severe asthma,¹¹⁸ and in people with other chronic respiratory diseases (this disease grouping included individuals with COPD, fibrosing lung disease, bronchiectasis, or cystic fibrosis).¹⁴ After hospital admission for COVID-19, individuals with pre-existing conditions have an increased risk of adverse respiratory sequelae,¹¹⁹ including an increased risk of death from lower respiratory tract infection and other respiratory complications.¹²⁰ Among people admitted to hospital or managed in the community for COVID-19, increased respiratory symptoms and increased inhaler use after COVID-19 have been reported in those with asthma or COPD, but whether this is due to a worsening of asthma or COPD control or to post-COVID-19-related symptoms is unclear.¹²¹

For more on HEAL-COVID see
<https://heal-covid.net/>

For more on STIMULATE-ICP see
<https://www.stimulate-icp.org/>

Several studies have included serial lung function testing up to 1 year after COVID-19.^{24,122–127} The group mean data from these studies consistently show a normal ratio of FEV₁ to forced vital capacity, with a normal forced expiratory flow rate between 25% and 75% of maximum when reported. The largest of these studies reported that 10% of participants had evidence of airflow obstruction, but this was in keeping with the proportion that had pre-existing obstructive lung disease.¹²⁵ By contrast, most of these studies reported abnormal lung diffusion in approximately a third of patients. Similarly, imaging studies have identified abnormalities in thoracic CT in up to 25% of cases after 1-year follow-up.⁶⁹ In people with persistent dyspnoea at 6 months after COVID-19 with normal thoracic CT and lung function, exploratory hyperpolarised ¹²⁹Xe MRI has shown damage to the alveolar–capillary interface, possibly contributing to their breathlessness,¹¹⁴ but again suggesting that this is not due to new obstructive lung disease.

Post-infective bronchiectasis might be predicted following COVID-19. In contrast to the 2009 H7N9 influenza A pandemic, when bronchiectasis was reported in 24% of survivors,¹²⁸ bronchiectasis was rarely observed after SARS-CoV infection and was present in about 1% of cases 1 year after COVID-19 in a study from Wuhan, China.¹²⁶ Intriguingly, SARS-CoV-2 viral entry and replication is impaired in cystic fibrosis airways owing to ACE2 downregulation mediated by dysfunctional cystic fibrosis transmembrane conductance regulator.¹²⁹ This is consistent with the observation that having cystic fibrosis is not a risk factor for acute severe COVID-19 disease and that lung function is stable after infection compared with pre-existing disease.^{130,131}

Extrapulmonary sequelae of COVID-19

Extrapulmonary sequelae of COVID-19 are wide-ranging, affecting multiple organ systems. We highlight extrapulmonary features of long COVID that might contribute to breathlessness and breathing pattern disorders and could be targeted as part of comprehensive therapeutic and rehabilitative strategies.

Reduced exercise tolerance

As for many other long-term conditions, reduced exercise tolerance is an important factor in the symptoms and functional limitations seen after COVID-19. The mechanisms that contribute to this reduction in exercise tolerance are not known, but bed rest in otherwise healthy individuals results in rapid-onset muscle wasting,¹³² reduced muscle endurance, and denervation.^{133,134} Even more profound muscle loss is seen in the inpatient hospital setting, particularly in ICUs, where the additional mechanisms of inflammation, hypoxia, and nutritional imbalance might be involved.^{135,136} Thus, it is likely that deconditioning contributes to the reduction in exercise tolerance seen after COVID-19. The potential role of deconditioning has been explored using

cardiopulmonary exercise testing, which shows response patterns that are consistent with the presence of reduced muscle aerobic capacity.^{137,138} In a Norwegian cohort, 12 months after hospital discharge for COVID-19, the most prevalent exercise limitation was deconditioning, defined as a percentage of predicted peak oxygen uptake of less than 80% in the absence of a ventilatory limitation and with no evidence of cardiocirculatory pathology. Reductions in the capacity for aerobic ATP generation usually occur with a reduction in the gas-exchange threshold, meaning that aerobic mechanisms of energy provision are supplemented with less efficient anaerobic mechanisms at a lower level of oxygen uptake. When the gas-exchange threshold is exceeded, the oxygen cost of exercise is increased, causing an increase in ventilation and consequently the sensation of breathlessness. Prolonged symptoms of fatigue and breathlessness commonly continue into the post-acute phase of COVID-19, and propagate a downward spiral of further inactivity, decreasing exercise tolerance, increasing sedentary behaviour, and further worsening of deconditioning and symptoms.²⁴

Frailty

Physical deconditioning leads to associated loss of muscle mass and strength, which could have profound consequences, especially in elderly individuals, predisposing them to physical frailty. Frailty refers to an increased risk of adverse health outcomes due to reduced resistance to stressor events.¹³⁹ COVID-19, as with other acute infectious diseases, provides a stressor that has been both severe and extremely widespread among individuals who were frail before their illness or who are at risk of becoming frail. Early studies indicate that 20% of COVID-19 survivors will have or will be at risk of frailty¹⁴⁰ and, as in chronic respiratory diseases, frailty is closely associated with the degree of dyspnoea.¹⁴¹

The clinical management of frailty relies on the identification of individuals living with frailty and, more widely, those at risk of developing frailty. The comprehensive geriatric assessment¹⁴² provides a well established framework from which assessments can be made, although modifications in focus might be important given the younger age demographic and more specific stressor event for COVID-19 survivors living with frailty.¹⁴³ Key domains that should be assessed include physical inactivity, weakness, polypharmacy, low mood, and social isolation, with clear pathways and management strategies available for onward referral.¹⁴⁰ Wider recognition of social inequality is also crucial in the review of people after COVID-19, because it is a major risk factor for both infection¹⁴⁴ and the presence of physical frailty.¹⁴³

Recent evidence has indicated that unintentional weight loss is the most common contributor to the physical frailty phenotype in the first 6 months after hospital admission for COVID-19, highlighting the need for nutritional assessment and intervention.¹⁴³ However, this should be

considered in the context of a raised BMI in many people who are admitted to hospital with COVID-19,²⁴ so simply increasing nutritional intake is not the solution. Other drivers of frailty in this cohort include dyspnoea, low physical activity, and muscle weakness.^{112,143} These findings combined with other data highlighting the high frequency of persistent breathlessness, muscle weakness, and fatigue,⁶⁹ as well as low mood and cognitive impairment,²⁴ indicate that a comprehensive assessment with provision for interventions addressing these areas would be optimal.

The potential contribution of pulmonary and extrapulmonary sequelae described in this Series paper to breathlessness in COVID-19 survivors is shown in figure 3. Non-pharmacological interventions might help to attenuate the disabling sensations of breathlessness in people with post-COVID-19 condition.

Assessment of breathlessness and altered breathing patterns

Breathlessness is a complex symptom that is inconsistently predicted from measures of lung function. In cases with a pathologically driven deficit, treatment

with bronchodilators, for example, does not necessarily ameliorate breathlessness. The complexity of breathlessness has been described in the Breathing, Thinking, Functioning clinical model,¹⁴⁵ which acknowledges that this debilitating symptom can be influenced by physiology (including pre-existing respiratory conditions), anxiety, previous experiences of breathlessness, and the level of function (including deconditioning). Importantly, the relative contribution of all these factors can vary between individuals. This model was developed for chronic respiratory disease but resonates for those with breathlessness after COVID-19.

The treatment of breathlessness should be guided by a detailed assessment that includes routine spirometry; however, there has been a paucity of data on lung function after COVID-19 owing to pandemic restrictions and the need for personalised protective equipment in health-care settings. Even one of the largest cohort studies of patients admitted to hospital performed lung function tests in only 349 (20·1%) of 1733 participants at 6 months after discharge,²⁷ and testing is likely to be biased towards adults with a clinical indication, including those with pre-existing

For more on the **Breathing, Thinking, Functioning model** see <https://www.btf.phpc.cam.ac.uk/>

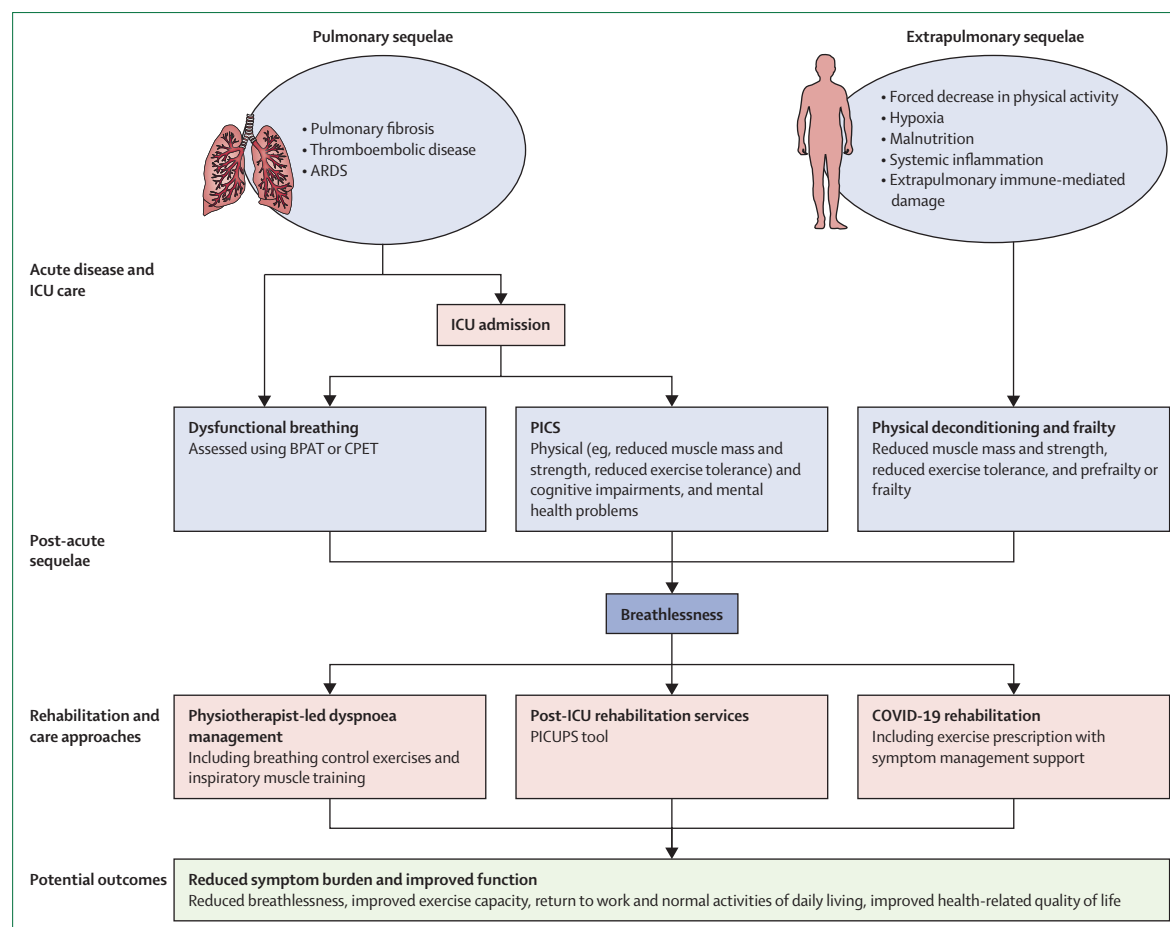


Figure 3: Potential origins of persistent breathlessness and proposed rehabilitation and care approaches

ARDS=acute respiratory distress syndrome. BPAT=Breathing Pattern Assessment Tool. CPET=cardiopulmonary exercise test. ICU=intensive care unit. PICS=post-intensive care syndrome. PICUPS=Post-ICU Presentation Screen.

respiratory disease. The assessment should also include validated questionnaires; the Borg Breathlessness Scale or MRC Dyspnoea Scale are commonly used, but do not capture the sensations of breathlessness such as muscle work or effort, mental effort, air hunger, chest tightness, and hyperventilation. By contrast, questionnaires such as Dyspnoea-12 or the Multi-Dimensional Dyspnoea Profile explore the multidimensional components of breathlessness.^{146,147} Cardiopulmonary exercise testing might also be indicated in cases of diagnostic uncertainty relating to breathlessness, and more complex investigations such as MRI and electromyography might be considered. Hyperpolarised ¹²⁹Xe MRI can be used to identify changes in gas transfer and tissue plasma abnormalities that might contribute to the breathlessness presentation,¹⁴⁸ whereas electromyography has been used to demonstrate increased inspiratory muscle activation after COVID-19, which might indicate underlying interstitial pathology, myopathy, deconditioning, or anxiety.¹⁴⁹

Acute COVID-19 can lead to altered breathing patterns, with small cohort studies reporting altered breathing patterns in almost 20% of people admitted to hospital with COVID-19 and a slightly greater proportion of people not admitted to hospital being referred to specialist follow-up clinics.^{150,151} Breathing pattern abnormalities can be attributed to changes in lung function, effects of sedation on respiratory centres, effects of mechanical ventilation, health-related anxiety, and the wearing of masks or personal protective equipment.¹⁵⁰ Tools to assess altered breathing patterns include the Nijmegen Questionnaire (specifically for hyperventilation syndrome) and the Breathing Pattern Assessment Tool (BPAT).^{152,153} The BPAT has a sensitivity and specificity of 90% and 78%, respectively, in diagnosing breathing pattern disorder in COVID-19.¹⁵⁴ Cardiopulmonary exercise testing can be used to support the diagnosis of a breathing pattern disorder, including hyperventilation, where a submaximal test result might be noted alongside an abnormal breathing pattern.¹⁵⁵ Specifically, in post-COVID-19 condition, cardiopulmonary exercise testing has been used to identify dysfunctional breathing in 30% of patients when it is defined as hyperventilation (an elevated minute ventilation to CO₂ output ratio) or an erratic breathing pattern (high variability in tidal volume, breathing frequency, or both) in the absence of a respiratory limitation or impairment in oxygen delivery or use.¹⁵⁶ A systematic review of cardiopulmonary exercise testing in post-COVID-19 condition reported a lower peak oxygen uptake in individuals with persistent breathlessness compared with those who had a full recovery after COVID-19; although deconditioning was the most common pattern, breathing pattern disorder was also commonly reported.¹⁵⁷

Rehabilitation and care approaches

The management of respiratory symptoms in the population with post-COVID-19 condition falls broadly into two categories: supervised group exercise

rehabilitation programmes (adapted pulmonary rehabilitation) or individual, largely physiotherapy-based, approaches to dyspnoea management that focus on breathing control. There is a paucity of data describing effective management strategies for post-COVID-19 condition, particularly from low-income and middle-income countries. In this section, we explore post-ICU rehabilitation and rehabilitation for chronic respiratory disease that might inform long COVID services, before discussing approaches to attenuate breathlessness, including physiotherapy-based strategies, in patients recovering from COVID-19.

Post-ICU rehabilitation

Literature on the wider experience of critical illness can inform recovery services for the minority of patients with COVID-19 who require critical care. In 2009, the UK National Institute for Health and Care Excellence published the first clinical guideline detailing rehabilitation strategies for patients who survive an episode of critical illness.¹⁵⁸ The Faculty of Intensive Care Medicine has issued further guidance on the delivery of post-ICU services, incorporating learning from the COVID-19 pandemic.¹⁵⁹ A recent survey of UK hospitals reported that more than 70% had inpatient multidisciplinary post-ICU recovery services and outpatient services, demonstrating a substantial expansion of service provision compared with a previous national survey in 2013.¹⁶⁰ Despite these guidelines, there is wide variability in models of care for the organisation of post-intensive care services.

The evidence base for rehabilitation outcomes after critical illness interventions is weak. A wide range of interventions and follow-up services that aim to improve recovery after critical illness across the three domains of post-intensive care syndrome (physical, psychosocial, and cognitive) has been studied. For example, interventions targeting the physical health domain have included outpatient physical therapy, nutritional support, provision of a rehabilitation manual, and home-based rehabilitation.¹⁶¹ However, two Cochrane systematic reviews evaluating interventions demonstrated insufficient evidence of effectiveness for a range of post-ICU outcomes.^{162,163}

For this reason, post-ICU recovery guidelines largely focus recommendations on processes of care, such as tailored clinical assessment, systematic screening for rehabilitation needs, and information sharing, rather than on specific interventions.¹⁵⁸ One recently published screening tool, the Post-ICU Presentation Screen (PICUPS), was developed by the UK National Post-ICU Rehabilitation Collaborative, which combined experts in critical care and rehabilitation medicine to address the needs of the greater number of patients seen in ICUs due to COVID-19.¹⁶⁴ The 14-item PICUPS checklist supports the handover of rehabilitation needs between health-care teams, facilitates the identification of

problems that warrant more detailed assessment or referral for specialist support, and informs the development of a rehabilitation prescription.

Chronic respiratory disease rehabilitation

A large body of evidence supports the use of pulmonary rehabilitation as a key intervention to reduce breathlessness in COPD. The main outcomes are a reduction in breathlessness, psychological stress (anxiety and depression), and fatigue, and improved health-related quality of life and exercise capacity.¹⁶⁵ Evidence is emerging for a similarly structured rehabilitation programme for individuals with ILD. The data identify a significant and meaningful improvement in exercise capacity (measured using the 6-min walk test) and health-related quality of life.¹⁶⁶ An updated Cochrane review highlighted the longer-term benefits of this intervention with gains extending to 12 months in patients with ILD compared with a control (usual care) group.¹⁶⁶ Several studies have described rehabilitation in the management of pulmonary hypertension, most of which have focused on highly supervised rehabilitation; along with safety, benefits have been reported for important outcomes such as functional capacity and breathlessness.¹⁶⁷ Finally, for people with a pre-existing respiratory disease and frailty, evidence suggests that a pulmonary rehabilitation programme can positively shift the categorisation of frailty from frail to prefrail;¹⁶⁸ however, the acceptability of this format might be limited owing to a higher dropout rate in the frail compared with the non-frail group.

The management of exercise-induced oxygen desaturation, which can be profound in some individuals, has been a safety concern in ILD and similar concerns have been reported in post-COVID-19 condition.¹⁶⁹ However, the prevalence of desaturation at follow-up after COVID-19 appears to be low and is not necessarily associated with impaired functional capacity.¹⁷⁰ The American Thoracic Society clinical practice guideline on home oxygen therapy for individuals with exertional hypoxaemia (pulse-oximetric oxygen saturation $\leq 88\%$) includes a conditional recommendation for treatment with ambulatory oxygen, but this is based on low-quality evidence.¹⁷¹ The management of exertional desaturation in post-COVID-19 condition has not been widely studied yet, but a pragmatic approach would be to use ambulatory oxygen in patients who benefit once underlying causes have been managed.

Post-COVID-19 condition rehabilitation

The use of exercise-based rehabilitation programmes (adapted pulmonary rehabilitation) for people with post-COVID-19 condition might be beneficial for symptoms of breathlessness in those with no contraindications to exercise therapy. Rehabilitation was recommended early in the pandemic, particularly for individuals with breathlessness, including those managed

in primary care.^{172–174} To date, few evidence-based therapeutic options for breathlessness have been developed and tested for the population with post-COVID-19 condition.¹⁷⁵ However, this has been identified as a research priority by all key stakeholders.¹⁷⁶ Within the limited body of research, there is evidence of the feasibility and safety of rehabilitation for people with post-COVID-19 condition, including face-to-face and digital modes of delivery.^{177–179} The advantages and disadvantages of these rehabilitation modes need to be addressed in the context of health-care systems, but transport, social circumstances, and digital literacy are also important considerations. At present, great heterogeneity exists between rehabilitation programmes, but common components include aerobic exercise, resistance exercise, and education on symptom management. A recent systematic review on the effects of pulmonary rehabilitation including exercise programmes showed improvements in dyspnoea, physical function, and quality of life after the programme in patients with post-COVID-19 condition;^{175,180} however, patients should be selected carefully according to their symptom profiles and monitored while undergoing exercise-based rehabilitation. Moreover, there is a need for further research with high-quality evidence, particularly including people who were not admitted to hospital for COVID-19.

Studies of other strategies for the management of breathlessness in post-COVID-19 condition have included an online singing-based programme delivered by the English National Opera that targeted people with breathlessness,¹⁸¹ and an inspiratory muscle training programme,¹⁸² both of which were home-based. In the former study,¹⁸¹ participants' mental health showed improvements on the 36-item Short-Form Survey, but there was no change in the physical component of this scale. Importantly, the sensation of breathlessness was reduced. Inspiratory muscle training led to a reduction in the breathlessness component of the King's Brief Interstitial Lung Disease Questionnaire, a health-related quality-of-life questionnaire, but the overall questionnaire score was unchanged.¹⁸² The mean predicted maximum inspiratory pressure improved from 92% to 109% after the intervention.

To date, the effectiveness of breathing exercises and retraining after acute COVID-19 has not been established. Breathing exercises are widely used for breathing pattern disorder in people with and without respiratory disease. A review broadly supported the use of breathing exercises in COPD, leading to improved exercise capacity but with no effect on breathlessness.¹⁸³ A Cochrane review of breathing exercises,¹⁸⁴ including brief physiotherapy interventions,¹⁸⁵ for the management of asthma showed favourable outcomes. However, another Cochrane review found no clear evidence to support the use of breathing exercises in people with breathing pattern disorder (dysfunctional breathing).¹⁸⁶ While evidence is being accumulated, it should be recognised that breathing

exercises are generally deemed to be low risk for people with non-COVID-19-related breathlessness, might be valuable for people with breathlessness after COVID-19, and have been proposed by WHO for the management of post-COVID-19 condition.¹⁸⁷

Conclusion

The consequences of SARS-CoV-2 infection and COVID-19 are far-reaching, and the effects on the respiratory system have been an important focus in the post-COVID-19 landscape. Respiratory symptoms, including breathlessness and breathing pattern disorders, are a common feature of post-COVID-19 condition; cough, which is

highly prevalent during acute illness, is less prevalent in post-COVID-19 condition. Specific pulmonary sequelae of COVID-19 (pulmonary fibrosis and thromboembolic disease) need careful assessment and might require specific investigations and treatments. A combination of pulmonary and extrapulmonary sequelae (eg, reduced exercise tolerance and frailty) might contribute to persistent and disabling breathlessness in people with post-COVID-19 condition; rehabilitation strategies for post-ICU syndrome and chronic respiratory conditions are informing services for people with this condition.

Further research is needed to understand pulmonary sequelae and extrapulmonary disruption leading to breathlessness; studies should aim to characterise long-term complications in more detail, and to determine the incidence, mechanisms of injury, and optimum diagnostic and management approaches specifically for post-COVID-19 condition to improve outcomes in this population. Key questions for future research are presented in the panel. To date, non-pharmacological options modified from those used in other respiratory conditions have focused on breathing control, respiratory pattern training, inspiratory muscle training, and exercise-based rehabilitation delivered in various formats. While research into the effectiveness of non-pharmacological interventions is ongoing, patients with post-COVID-19 condition can best be supported by an integrated multidisciplinary team. Respiratory and rehabilitation specialists should be at the core of this team, using therapeutic and rehabilitative strategies tailored to the symptom profiles and needs of individual patients, ensuring that culturally appropriate, equitable access is provided to accommodate diverse populations.

Contributors

The manuscript was initially developed by SJS; contributions were drafted by all authors and further developed by SJS, MMB, CEB, and RAE. All authors contributed to critical review and revision of the manuscript. All authors had final responsibility for the decision to submit for publication.

Declaration of interests

SJS has received project funding from the UK National Institute for Health Research (NIHR), UK Research and Innovation, the Department of Health and Social Care, and Actegy. She has received funding for a doctoral training programme from the Wellcome Trust, and reports funding for presentations from GSK, the UK Ministry of Justice, Cipla, and Sherbourne Gibbs. SJS is the American Thoracic Society Pulmonary Rehabilitation Assembly Chair, clinical lead for the Royal College of Physicians Pulmonary Rehabilitation Accreditation Scheme, clinical lead for the National Asthma and COPD Audit Programme for Pulmonary Rehabilitation, and is on the National Institute for Health and Care Excellence expert advisory panel for long COVID. CEB has received funding to his institution for consultancy and investigator roles from GSK, AstraZeneca, Genentech, Roche, Sanofi, Regeneron, Boehringer Ingelheim, Chiesi, Mologic, and 4DPharma. RAE reports research funding from the NIHR, UKRI, and the Wolfson Foundation. She has received payment for a consultancy role from AstraZeneca, for invited lectures from Boehringer Ingelheim, and for conference attendance from Chiesi. RAE is secretary of the European Respiratory Society Group 01.02 Rehabilitation and Chronic Care. RGJ has received grants to his institution from AstraZeneca, Biogen, Galecto, GSK, Nordic Biosciences, RedX, and Pilant. He reports consultancy fees from AstraZeneca, Brainomix, Bristol Myers Squibb, Chiesi, Cohbar, Daewoong, GSK, Pilant,

Panel: Research priorities

- What are the underlying mechanisms of post-COVID-19 condition that drive the symptom of breathlessness?
- What is the optimal treatment for acute COVID-19 to mitigate, or even prevent, the development of pulmonary fibrosis?
- Is thrombosis that is associated with COVID-19 phenotypically distinct from classic thromboembolic disease? If so, what are the treatment and prognostic implications of phenotypic clinical and biological differences?
- What is the optimal diagnostic or imaging modality for detection of post-COVID-19 pulmonary vascular disease?
- What are the mechanisms that underpin reduced asthma and COPD control after COVID-19?
- What is the incidence of extrapulmonary complications (eg, frailty, sarcopenia) that contribute to breathlessness after COVID-19?
- Are rehabilitation or breathing exercises effective strategies for reducing breathlessness in people with post-COVID-19 condition?

Search strategy and selection criteria

We searched PubMed (MEDLINE) and CINAHL for articles published in English from database inception to March 15, 2023. Combinations of the following terms were used in the searches: "COVID-19", "COVID", "SARS-CoV-2", "thromboembolic disease", "pulmonary embolism", "venous thrombosis", "microvascular", "immunothrombosis", "pulmonary vascular", "CTEPH", "pulmonary fibrosis", "acute respiratory distress syndrome", "ARDS", "rehabilitation", "frailty", "dysfunctional breathing", and "disordered breathing". The abstracts of original investigations and review articles and the references of selected studies were screened and included on the basis of relevance to the topics covered in this Series paper. We searched ClinicalTrials.gov for active and planned clinical trials of investigational medicinal products that might have antifibrotic effects in COVID-19 populations using the following terms: "COVID-19", "COVID", "pulmonary fibrosis", "fibrotic", "fibrotic lung disease", and "post-COVID fibrosis".

Resolution Therapeutics, Roche, and Veracyte, and lecture fees from AstraZeneca, Boehringer Ingelheim, Chiesi, Roche, and PatientMPower. RGJ is on data safety monitoring boards for Boehringer Ingelheim, Galapagos, and Vicore, and is on the advisory board of NuMedii. RGJ is the current president of Action for Pulmonary Fibrosis. MT has received funding from MorphogenIX and Jansen for taking part in advisory boards and has received support from GSK and Jansen to travel and attend meetings. All other authors declare no competing interests.

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