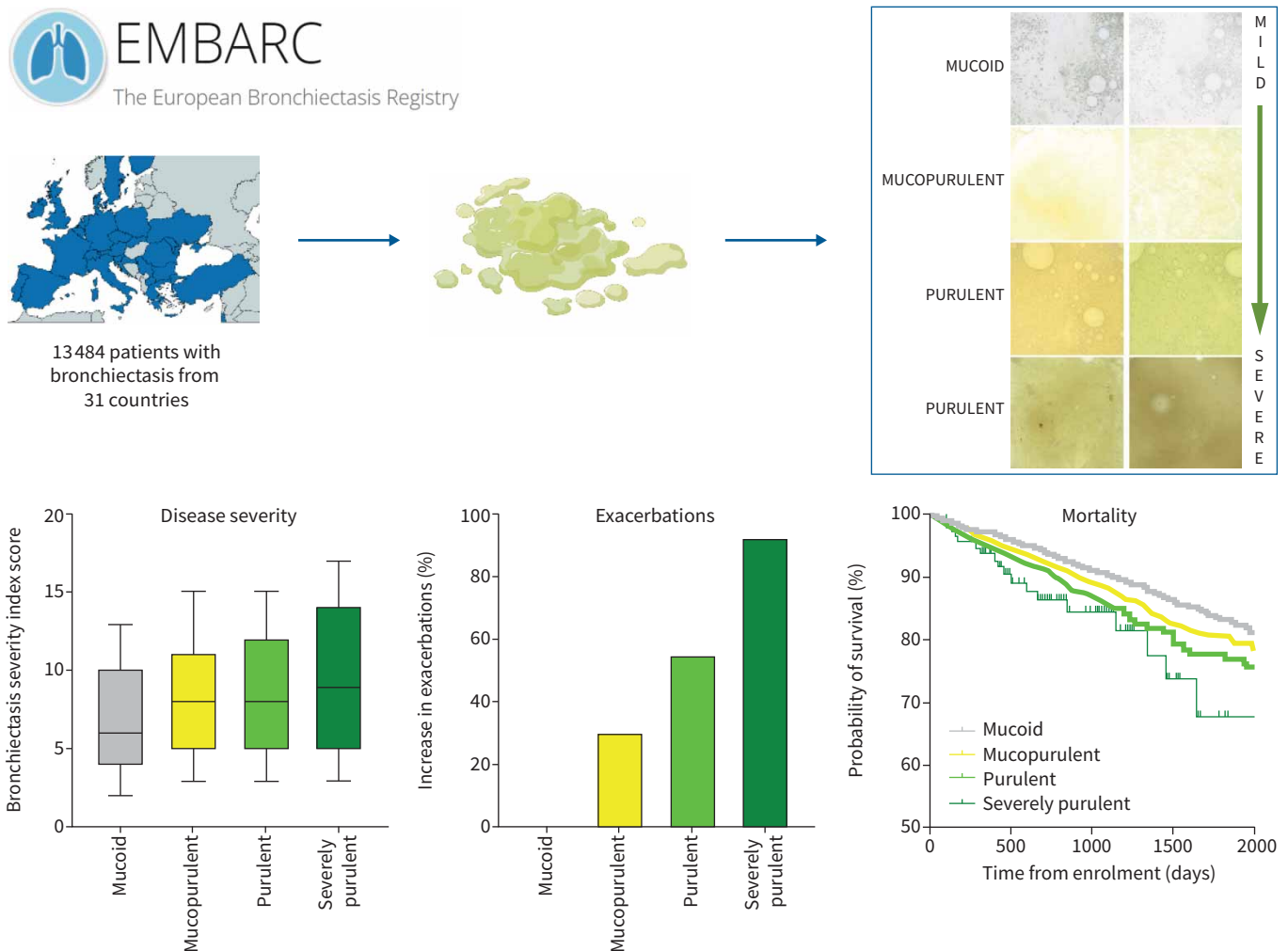




Objective sputum colour assessment and clinical outcomes in bronchiectasis: data from the European Bronchiectasis Registry (EMBARC)

Stefano Aliberti ¹, Felix C. Ringshausen ², Raja Dhar, Charles S. Haworth, Michael R. Loebinger, Katerina Dimakou, Megan L. Crichton, Anthony De Soya ³, Montse Vendrell, Pierre-Regis Burgel ⁴, Melissa McDonnell ⁵, Sabina Skrgat, Luis Maiz Carro, Andres de Roux, Oriol Sibila, Apostolos Bossios ⁶, Menno van der Eerden, Paula Kauppi, Robert Wilson, Branislava Milenkovic, Rosario Menendez, Marlene Murriss, Sermin Borekci, Oxana Munteanu, Dusanka Obradovic, Adam Nowinski, Adelina Amorim, Antoni Torres ⁷, Natalie Lorent ⁸, Eva Van Braeckel ⁹, Josje Altenburg, Amelia Shoemark ¹⁰, Michal Shteinberg ¹¹, Wim Boersma, Pieter C. Goeminne, J. Stuart Elborn, Adam T. Hill, Tobias Welte ¹², Francesco Blasi, Eva Polverino and James D. Chalmers on behalf of the EMBARC Registry Investigators



GRAPHICAL ABSTRACT We enrolled 13 484 patients with bronchiectasis from 31 countries. Assessment of sputum colour at baseline was used to investigate the relationship with disease severity and outcomes. We show a strong relationship between sputum colour and exacerbations and hospitalisation for severe exacerbations. Increasing sputum purulence is a marker of disease outcome in bronchiectasis.



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¹Respiratory Unit, IRCCS Humanitas Research Hospital, Pieve Emanuele, Italy. ²Department of Biomedical Sciences, Humanitas University, Pieve Emanuele, Italy. ³Department of Respiratory Medicine and Infectious Diseases, Hannover Medical School, Hannover, Germany. ⁴Biomedical Research in End-Stage and Obstructive Lung Disease Hannover, German Center for Lung Research (DZL), Hannover, Germany. ⁵European Reference Network on Rare and Complex Respiratory Diseases, Frankfurt, Germany. ⁶CK Birla Hospitals, Kolkata, India. ⁷Cambridge Centre for Lung Infection, Royal Papworth Hospital and University of Cambridge, Cambridge, UK. ⁸Royal Brompton and Harefield Hospitals and National Heart and Lung Institute, Imperial College London, London, UK. ⁹5th Respiratory Department and Bronchiectasis Unit, “Sotiria” General Hospital of Chest Diseases Medical Practice, Athens, Greece. ¹⁰Division of Molecular and Clinical Medicine, University of Dundee, Ninewells Hospital and Medical School, Dundee, UK. ¹¹Population and Health Science Institute, Newcastle University and NIHR Biomedical Research Centre for Ageing, Freeman Hospital, Newcastle, UK. ¹²Department of Pulmonology, Dr Trueta University Hospital, Girona Biomedical Research Institute (IDIBGI), University of Girona, Girona, Spain. ¹³Department of Respiratory Medicine and French Cystic Fibrosis National Reference Center, Hôpital Cochin, AP-HP, Paris, France. ¹⁴Université Paris Cité, Inserm U1016, Institut Cochin, Paris, France. ¹⁵Department of Respiratory Medicine, Galway University Hospital, Galway, Ireland. ¹⁶University Clinic of Respiratory and Allergic Diseases Golnik, Golnik, Slovenia. ¹⁷Medical Faculty, University of Ljubljana, Ljubljana, Slovenia. ¹⁸Division of Internal Medicine, Pulmonary Department, University Medical Centre Ljubljana, Ljubljana, Slovenia. ¹⁹Chronic Bronchial Infection Unit, Pneumology Service, Ramón y Cajal Hospital, Alcalá de Henares University, Madrid, Spain. ²⁰Pneumologische Praxis am Schloss Charlottenburg, Berlin, Germany. ²¹Servicio de Neumología, Instituto Clínico de Respiratorio, IDIBAPS, Hospital Clínic, University of Barcelona, Barcelona, Spain. ²²CIBER de Enfermedades Respiratorias, Instituto de Salud Carlos III, Madrid, Spain. ²³Department of Respiratory Medicine and Allergy, Karolinska University Hospital, Stockholm, Sweden. ²⁴Division of Lung and Airway Research, Institute of Environmental Medicine, Karolinska Institutet, Stockholm, Sweden. ²⁵Erasmus MC, Department of Respiratory Medicine, Rotterdam, The Netherlands. ²⁶Heart and Lung Center, Helsinki, Finland. ²⁷Clinic for Pulmonary Diseases, University Clinical Center of Serbia, Belgrade, Serbia. ²⁸School of Medicine, University of Belgrade, Belgrade, Serbia. ²⁹Pneumology Department, Hospital Universitario y Politécnico La Fe – Instituto de Investigación Sanitaria La Fe, Valencia, Spain. ³⁰Department of Respiratory Diseases, CHU Toulouse, Toulouse, France. ³¹Department of Pulmonology Diseases, Cerrahpasa Medical Faculty, Istanbul University – Cerrahpasa, Istanbul, Turkey. ³²Pneumology/Allergology Division, University of Medicine and Pharmacy Nicolae Testemitanu, Chisinau, Moldova. ³³Faculty of Medicine Novi Sad, University of Novi Sad, Novi Sad, Serbia. ³⁴Institute for Pulmonary Diseases, Sremska Kamenica, Serbia. ³⁵Department of Epidemiology, National Tuberculosis and Lung Diseases Research Institute, Warsaw, Poland. ³⁶Pulmonology Department, Centro Hospitalar Universitário S. João and Faculty of Medicine, University of Porto, Porto, Portugal. ³⁷Department of Respiratory Diseases, University Hospitals Leuven, Leuven, Belgium. ³⁸Department of Internal Medicine and Paediatrics, Faculty of Medicine and Health Sciences, Ghent University, Ghent, Belgium. ³⁹Department of Respiratory Medicine, Ghent University Hospital, Ghent, Belgium. ⁴⁰Department of Pulmonary Diseases, Amsterdam University Medical Centers, Amsterdam, The Netherlands. ⁴¹Pulmonology Institute and CF Center, Carmel Medical Center, Haifa, Israel. ⁴²B. Rappaport Faculty of Medicine, Technion – Israel Institute of Technology, Haifa, Israel. ⁴³Department of Pulmonary Diseases, Northwest Clinics, Alkmaar, The Netherlands. ⁴⁴Department of Respiratory Disease, AZ Nikolaas, Sint-Niklaas, Belgium. ⁴⁵Faculty of Medicine, Health and Life Sciences, Queen’s University, Belfast, UK. ⁴⁶Department of Respiratory Medicine, Royal Infirmary of Edinburgh, Edinburgh, UK. ⁴⁷Department of Pathophysiology and Transplantation, University of Milan, Milan, Italy. ⁴⁸Fondazione IRCCS Ca’ Granda Ospedale Maggiore Policlinico, Milan, Italy. ⁴⁹Pneumology Department, Hospital Universitari Vall d’Hebron, Vall d’Hebron Institut de Recerca (VHIR), Vall d’Hebron Barcelona Hospital Campus, CIBERES, Barcelona, Spain.

Corresponding author: James D. Chalmers (j.chalmers@dundee.ac.uk)



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Sputum colour is a simple non-invasive marker of airway inflammation that identifies patients with bronchiectasis at higher risk of exacerbation, hospitalisation and mortality <https://bit.ly/3HczGxO>

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Abstract

Background A validated 4-point sputum colour chart can be used to objectively evaluate the levels of airway inflammation in bronchiectasis patients. In the European Bronchiectasis Registry (EMBARC), we tested whether sputum colour would be associated with disease severity and clinical outcomes.

Methods We used a prospective, observational registry of adults with bronchiectasis conducted in 31 countries. Patients who did not produce spontaneous sputum were excluded from the analysis. The Murray sputum colour chart was used at baseline and at follow-up visits. Key outcomes were frequency of exacerbations, hospitalisations for severe exacerbations and mortality during up to 5-year follow-up.

Results 13 484 patients were included in the analysis. More purulent sputum was associated with lower forced expiratory volume in 1 s (FEV₁), worse quality of life, greater bacterial infection and a higher bronchiectasis severity index. Sputum colour was strongly associated with the risk of future exacerbations during follow-up. Compared to patients with mucoid sputum (reference group), patients with mucopurulent sputum experienced significantly more exacerbations (incident rate ratio (IRR) 1.29, 95% CI 1.22–1.38; $p < 0.0001$), while the rates were even higher for patients with purulent (IRR 1.55, 95% CI 1.44–1.67; $p < 0.0001$) and severely purulent sputum (IRR 1.91, 95% CI 1.52–2.39; $p < 0.0001$). Hospitalisations for severe exacerbations were also associated with increasing sputum colour with rate ratios, compared to patients with mucoid sputum, of 1.41 (95% CI 1.29–1.56; $p < 0.0001$), 1.98 (95% CI 1.77–2.21; $p < 0.0001$) and 3.05 (95% CI 2.25–4.14; $p < 0.0001$) for mucopurulent, purulent and severely purulent sputum, respectively. Mortality was significantly increased with increasing sputum purulence, hazard ratio 1.12 (95% CI 1.01–1.24; $p = 0.027$), for each increment in sputum purulence.

Conclusion Sputum colour is a simple marker of disease severity and future risk of exacerbations, severe exacerbations and mortality in patients with bronchiectasis.

Introduction

Bronchiectasis is a chronic inflammatory disease [1, 2]. Although it is recognised that bronchiectasis is composed of multiple phenotypes and endotypes, inflammation has classically been regarded as neutrophilic and patients with higher levels of neutrophilic inflammation have been shown to have worse clinical outcomes [3–5].

Although there are composite severity and prognostic assessment tools for bronchiectasis, there are currently no direct measures of inflammation [5–7]. Direct measurement of neutrophilic inflammation is currently only possible in the research sphere and is difficult to implement in clinical practice [4, 8].

Therefore the most accessible measure of neutrophilic inflammation in bronchiectasis is thought to be the assessment of sputum colour [9, 10]. The green colour associated with sputum purulence in chronic inflammatory lung diseases is thought to result from accumulation of myeloperoxidase (MPO) released from granulocytes. The increase of sputum purulence therefore provides a non-invasive assessment of the extent of neutrophilic inflammation [11, 12].

Since colour perception is subjective, the assessment of sputum colour in clinical practice requires to be standardised. In 2009, MURRAY *et al.* [9] developed a sputum colour chart for bronchiectasis patients based on sputum photographs which classifies samples into four groups. This study demonstrated an association between sputum colour and the presence of bacterial infection [9]. GOEMINNE *et al.* [10] extended these findings, demonstrating that neutrophilic inflammation and protease activity in sputum was directly related to sputum colour using this method. Existing data have, however, been derived from single-centre studies with small sample sizes. Prior studies did not investigate a possible correlation between the sputum colour chart and patients' clinical outcomes. Prior studies are therefore insufficient to establish that sputum colour assessment could be used for patient phenotyping in routine clinical practice.

To investigate the value of sputum colour assessment in identifying positive airway bacterial cultures, disease severity and risk of future exacerbations, we incorporated baseline and annual assessment of sputum colour using a standardised sputum colour chart into the data collected as part of the European



Bronchiectasis Registry (EMBARC) [13]. We tested whether a single assessment of sputum colour could identify the risk of airway infection, severity of disease and risk of future exacerbations.

Methods

EMBARC is a prospective observational study of patients with computed tomography (CT)-confirmed bronchiectasis conducted across more than 30 countries worldwide [13, 14]. The registry includes European Union (EU) countries, non-EU European countries and several non-European countries (Israel, India, Kyrgyzstan and Pakistan) [14, 15]. The study is approved by the ethical committee in the host country (UK) and by institutional review boards or ethics committees in all countries and regions in which the study is conducted. A detailed protocol of the study and baseline patient characteristics have been previously published [13, 14].

Data collection

Patient enrolment commenced in January 2015 and recruitment is open-ended and ongoing. Patients enrolled up to April 2022 were included for the purposes of this analysis. Patient data were collected annually using a standardised case report form. Comprehensive clinical data incorporating demographics, comorbidities, medications, aetiological testing, microbiology, radiology, lung function and disease history were recorded. Spirometry was performed according to American Thoracic Society/European Respiratory Society standards [16]. Aetiology was recorded by the investigators and verified using data on results of aetiological testing. Microbiology data from clinically indicated sputum samples sent during clinical stability and exacerbation were collected and patients classified according to whether they had specific bacteria isolated in any sample in the 12 months prior to the baseline visit. Radiological severity was evaluated in the patient's most recent CT scan using the modified Reiff score as previously described [17]. Disease severity was evaluated using the bronchiectasis severity index (BSI) with a sensitivity analysis performed using the FACED tool [7]. Exacerbations were defined as use of antibiotics for acute respiratory symptoms and were recorded from a combination of patient history, hospital and prescription records [18]. Severe exacerbations were defined as exacerbations requiring hospitalisation. Symptoms were evaluated using the Quality of Life Questionnaire-Bronchiectasis (QOL-B) version 3.1 using validated translations [19, 20].

Sputum colour assessment

Baseline and annual follow-up visits were performed during clinical stability. Sputum samples from these visits were used for sputum colour assessment by either the physician or patient using the chart developed by MURRAY *et al.* [9] (figure 1). The study user guide asked the physicians to make an assessment of sputum colour on a fresh sputum sample wherever possible. If this was not possible, patients were asked to report the most common/typical colour of their sputum during stable state (away from both exacerbations and antibiotic courses). The reliability of this scoring system for assessment by both patients and physicians was established in the original validation study with an intraclass correlation coefficient of 0.83. The online data collection tool provided the sputum colour chart (figure 1) to allow scoring by investigators at sites. A numerical scoring system from 1 (mucoid) to 4 (severely purulent) was used as originally described.

For the purposes of this analysis any patient unable to produce sputum at baseline was excluded, but data from this subgroup are shown for comparison.

Long-term clinical outcomes

Data are collected for up to 5 years on an annual basis for calculation of clinical outcomes. Since patient enrolment began in 2015, patients have up to 5 years of follow-up at the time of writing, although the dataset includes patients enrolled through to 2021/2022 who have not yet had a follow-up visit. Statistical analysis of relevant end-points takes account of the duration of follow-up. Relevant clinical outcomes were survival, exacerbation frequency and risk of hospitalisation due to severe exacerbations.

Statistical analysis

Summary data are presented as median (interquartile range (IQR)). Comparisons of more than two groups were performed by the Kruskal–Wallis test. Exacerbation frequency and frequency of severe exacerbations requiring hospital admission over time were studied using a negative binomial model with time in study as an offset. Survival analysis was performed using Cox proportional hazards regression [14]. The proportional hazards assumption was assessed with log–log plots.

We observed a strong relationship between sputum colour and *Pseudomonas aeruginosa* infection and so present adjusted analyses of these models with *P. aeruginosa* infection included as a covariate. In addition, an analysis was performed adjusting the negative binomial model for prior exacerbations to determine if sputum

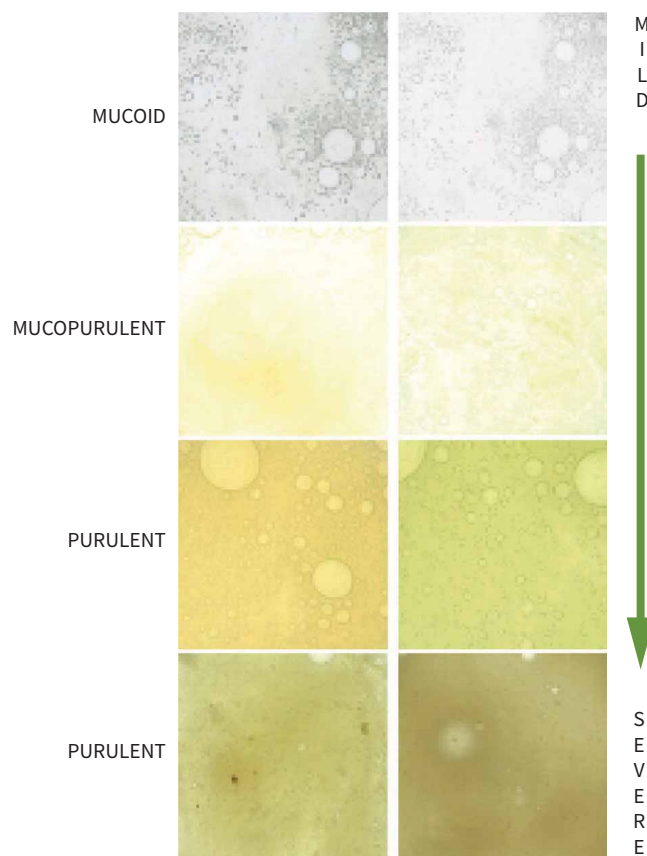


FIGURE 1 The Murray sputum colour chart. Reproduced from [9] with permission.

colour was associated with exacerbation risk after adjusting for prior exacerbation history. All analyses utilised SPSS version 27 (IBM, Armonk, NY, USA) or Prism version 9 (GraphPad, Boston, MA, USA).

Results

19 324 patients were enrolled from 31 countries. 13 484 patients reported daily sputum expectoration, had a sputum colour grade using the Murray chart performed and were, therefore, included in the analysis. This is shown in figure 2; a detailed description of the cohort is reported elsewhere [14]. Table 1 shows the characteristics of the patients at enrolment according to sputum colour at baseline (visit 1) including the characteristics of patients excluded as they did not regularly produce sputum.

Patients with more purulent sputum have a higher daily sputum volume, a higher modified Medical Research Council dyspnoea score, and a greater likelihood of prescription of macrolides, long-term antibiotics and inhaled antibiotics. No strong relationship was found between sputum colour and age, smoking status, or the presence of asthma or COPD as underlying conditions (table 1). Supplementary table S1 shows the relationships with aetiology, where the most common aetiologies did not have a greater odds of having purulent sputum compared to idiopathic bronchiectasis. Patients with primary ciliary dyskinesia or immunodeficiency had significantly higher odds of purulent sputum (supplementary table S1).

Relationship between sputum colour and severity of disease

Figure 3 shows the association between sputum colour and cross-sectional markers of bronchiectasis disease severity using the BSI. The BSI increased with increasing sputum colour from median (IQR) 6 (4–10) in patients with mucoid sputum to 8 (5–11) in patients with mucopurulent sputum, 8 (5–12) in patients with purulent sputum and 9 (5–14) in patients with severely purulent sputum. Similar results were seen with the FACED score (supplementary figure S1). Examining severity groups, we included 12 229 patients with complete data for analysis. Severe bronchiectasis classified by the BSI was observed in 1531 (31.5%) patients with mucoid sputum, 1992 (41.0%) patients with mucopurulent sputum, 1091 (46.3%) patients

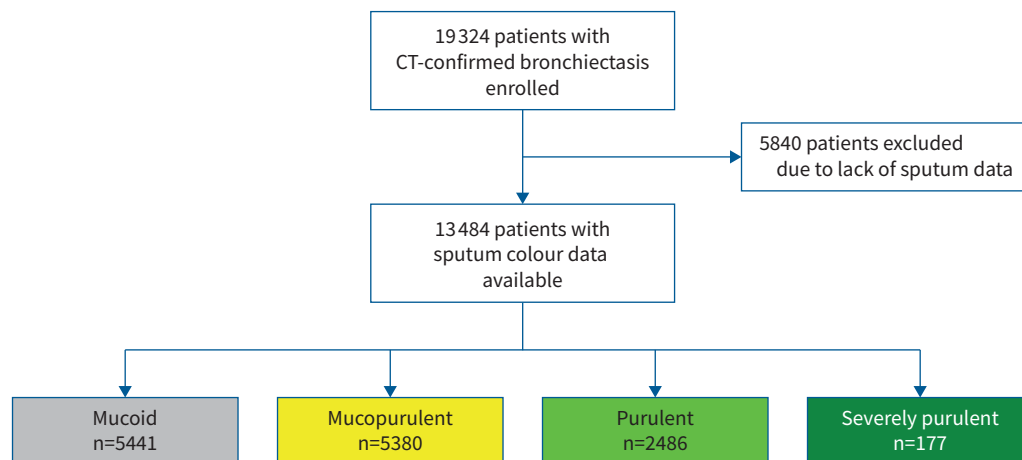


FIGURE 2 Flow of patients through the study. CT: computed tomography.

with purulent sputum and 81 (51.3%) patients with severely purulent sputum (supplementary table S2). Differences in disease severity were all statistically significant ($p < 0.0001$).

Forced expiratory volume in 1 s (FEV₁) percentage predicted was significantly lower in patients with more purulent sputum, with median values of 75.7%, 70.2%, 65.9% and 70.4% ($p < 0.0001$) for mucoïd, mucopurulent, purulent and severely purulent sputum, respectively (figure 3b). There were less obvious differences in radiological severity, with a median Reiff radiological severity score of 3 in patients with mucoïd sputum and 4 in patients with mucopurulent to severely purulent sputum ($p < 0.0001$) (figure 3c). The median (IQR) values of the QOL-B respiratory symptoms score were also strongly related to sputum colour, with patients with mucoïd sputum having the best quality of life (66.7 (48.1–77.8)), followed by patients with mucopurulent sputum (55.6 (40.7–70.4)), purulent sputum (48.1 (33.3–63.0)) and severely purulent sputum (44.4 (25.9–64.9)) ($p < 0.0001$) (figure 3d). Patients with purulent sputum also reported a larger daily sputum volume. Median (IQR) sputum volume was 10 (5–20) mL in patients with mucoïd sputum and 15 (10–30), 20 (10–50) and 30 (10–66) mL in patients with mucopurulent, purulent and severely purulent sputum, respectively.

Relationship between sputum colour and sputum culture

12 229 patients with complete data were included in this analysis. There was an increase in the percentage of patients with sputum samples positive for bacteria as sputum purulence increased. Figure 4 shows the frequency of the most common bacteria isolated in sputum at baseline. The frequency of additional pathogens is shown in supplementary table S3. 1279 (26.3%) patients with mucoïd sputum had a positive sputum for bacteria compared to 1863 (38.4%) with mucopurulent sputum, 1026 (43.5%) with purulent sputum and 84 (53.2%) with severely purulent sputum ($p < 0.0001$). Approximately a third of patients with purulent sputum and severely purulent sputum had isolation of *P. aeruginosa*. The EMBARC registry includes a data field for chronic *P. aeruginosa* infection and this also showed a clear increase with increasing sputum purulence, from 797 (16.4%) in patients with mucoïd sputum to 57 (36.1%) in patients with severely purulent sputum ($p < 0.0001$).

Significant differences were observed across sputum purulence categories for *P. aeruginosa* ($p < 0.0001$), *Haemophilus influenzae* ($p < 0.0001$), *Moraxella catarrhalis* ($p = 0.01$), Enterobacteriaceae ($p < 0.0001$), *Staphylococcus aureus* ($p < 0.0001$) and *Streptococcus pneumoniae* ($p < 0.0001$). *Aspergillus* species were observed in 110 (2.3%) patients with mucoïd sputum, 129 (2.7%) with mucopurulent sputum, 98 (4.2%) with purulent sputum and five (3.2%) with severely purulent sputum ($p < 0.0001$).

Relationship between sputum colour and exacerbations in the previous year

In the 12 months prior to the baseline visit there were 33 724 exacerbations in 12 229 patients with a valid sputum colour measurement and 6298 severe exacerbations requiring hospitalisation. The median (IQR) exacerbation frequency was 2 (1–4) per year.

Compared to patients with mucoïd sputum (reference group), exacerbation rates were increased with increasing sputum purulence, with rate ratios of 1.23 (95% CI 1.17–1.29), 1.38 (95% CI 1.31–1.47) and

TABLE 1 Patient characteristics according to baseline sputum colour[#]

| | Grade 1 (mucoïd) | Grade 2 (mucopurulent) | Grade 3 (purulent) | Grade 4 (severely purulent) | Non-sputum-producing patients |
|---|---------------------|---------------------------|-----------------------|--------------------------------|----------------------------------|
| Patients | 5441 (28.2) | 5380 (27.8) | 2486 (12.9) | 177 (0.9) | 5840 (30.2) |
| Demographics | | | | | |
| Age (years) | 66 (55–74) | 66 (55–74) | 66 (56–73) | 67 (57–75) | 65 (53–73) |
| Female | 3039 (55.9) | 3123 (58.0) | 1425 (57.3) | 97 (54.8) | 3712 (63.6) |
| BMI (kg·m ⁻²) | 24.6 (21.4–28.4) | 24.4 (21.4–28.2) | 24.2 (21.0–28.0) | 23.7 (20.7–28.5) | 24.4 (21.4–28.3) |
| Never-smoker | 3038 (55.8) | 3000 (55.8) | 1367 (55.0) | 89 (50.3) | 3325 (56.9) |
| Ex-smoker | 2031 (37.3) | 2052 (38.1) | 989 (39.8) | 77 (43.5) | 2156 (36.9) |
| Current smoker | 372 (6.8) | 328 (6.1) | 130 (5.2) | 11 (6.2) | 359 (6.1) |
| Comorbidity | | | | | |
| Cardiovascular disorders | 1685 (31.0) | 1729 (32.1) | 773 (31.1) | 64 (36.2) | 1672 (28.6) |
| Stroke | 169 (3.1) | 185 (3.4) | 73 (2.9) | 11 (6.2) | 171 (2.9) |
| Diabetes | 593 (10.9) | 573 (10.7) | 261 (10.5) | 22 (12.4) | 595 (10.2) |
| Liver disease | 36 (0.7) | 24 (0.4) | 16 (0.6) | 3 (1.7) | 43 (0.7) |
| Chronic renal failure | 181 (3.3) | 184 (3.4) | 102 (4.1) | 9 (5.1) | 218 (3.7) |
| COPD | 1428 (26.2) | 1450 (27.0) | 712 (28.6) | 49 (27.7) | 1243 (21.3) |
| Asthma | 1665 (30.6) | 1666 (31.0) | 732 (29.4) | 46 (26.0) | 1655 (28.3) |
| Osteoporosis | 649 (11.9) | 713 (13.3) | 337 (13.6) | 30 (16.9) | 634 (10.9) |
| Depression | 654 (12.0) | 763 (14.2) | 392 (15.8) | 48 (27.1) | 617 (10.6) |
| Solid tumour | 515 (9.5) | 530 (9.9) | 270 (10.9) | 19 (10.7) | 547 (9.4) |
| Aetiology | | | | | |
| Idiopathic | 1934 (35.5) | 1964 (36.5) | 876 (35.2) | 66 (37.3) | 2117 (36.3) |
| Post-infective | 1173 (21.6) | 1193 (22.2) | 571 (23.0) | 29 (16.4) | 1200 (20.5) |
| Tuberculosis | 538 (9.9) | 396 (7.4) | 149 (6.0) | 10 (5.6) | 533 (9.1) |
| Immunodeficiency | 177 (3.3) | 201 (3.7) | 110 (4.4) | 4 (2.3) | 214 (3.7) |
| ABPA | 179 (3.3) | 177 (3.3) | 79 (3.2) | 7 (4.0) | 226 (3.9) |
| Rheumatoid arthritis | 112 (2.1) | 159 (3.0) | 63 (2.5) | 8 (4.5) | 148 (2.5) |
| Others | 1328 (24.4) | 1290 (24.0) | 638 (25.7) | 53 (29.9) | 1402 (24.0) |
| Clinical status | | | | | |
| Sputum volume (mL·day ⁻¹) | 10 (5–20) | 15 (10–30) | 20 (10–50) | 30 (10–66) | 0 (0–0) |
| mMRC dyspnoea score [¶] | | | | | |
| 0 | 1425 (26.2) | 1069 (19.9) | 416 (16.7) | 34 (19.2) | 1864 (31.9) |
| 1 | 1776 (32.6) | 1727 (32.1) | 759 (30.5) | 42 (23.7) | 1945 (33.3) |
| 2 | 1188 (21.8) | 1343 (25.0) | 595 (23.9) | 34 (19.2) | 1172 (20.1) |
| 3 | 710 (13.0) | 859 (16.0) | 457 (18.4) | 37 (20.9) | 560 (9.6) |
| 4 | 279 (5.1) | 338 (6.3) | 219 (8.8) | 30 (16.9) | 207 (3.5) |
| Treatment | | | | | |
| Long-term macrolide treatment | 768 (14.1) | 995 (18.5) | 547 (22.0) | 36 (20.3) | 733 (12.6) |
| Other long-term oral antibiotic treatment | 228 (4.2) | 292 (5.4) | 202 (8.1) | 13 (7.3) | 196 (3.4) |
| Inhaled antibiotic treatment | 313 (5.8) | 523 (9.7) | 357 (14.4) | 31 (17.5) | 167 (2.9) |
| Inhaled corticosteroids | 2900 (53.3) | 3008 (55.9) | 1376 (55.3) | 86 (48.6) | 2739 (46.9) |

Data are presented as n (%) or median (interquartile range). BMI: body mass index; ABPA: allergic bronchopulmonary aspergillosis; mMRC modified Medical Research Council. [#]: all variables measured at baseline visit. [¶]: totals for mMRC dyspnoea score do not add up to 100% due to missing data.

1.51 (95% CI 1.26–1.81) for mucopurulent, purulent and severely purulent sputum, respectively. For severe exacerbations the relationship was even stronger, with rate ratios of 1.28 (95% CI 1.19–1.37), 1.63 (95% CI 1.50–1.77) and 1.68 (95% CI 1.31–2.15) for patients with mucopurulent, purulent and severely purulent sputum, respectively. This is shown in figure 5a.

At baseline, across the whole cohort, 2579 (21.1%) patients had no exacerbations, 2242 (18.3%) had 1 exacerbation per year, 2138 (17.5%) patients had 2 exacerbations per year and 5270 (43.1%) had ≥ 3 exacerbations per year. The proportion of patients with ≥ 3 exacerbations per year markedly increased with increasing sputum purulence from 36.0% (n=1751) in patients with mucoïd sputum to 45.8% (n=2225) in patients with mucopurulent sputum, 51.0% (n=1202) in patients with purulent sputum and 58.2% (n=92) in patients with severely purulent sputum (p<0.0001).

Sputum colour and long-term clinical outcomes

Long-term clinical outcomes were evaluated over a cumulative total of 29 830 years of patient follow-up (range 0–5 years per patient).

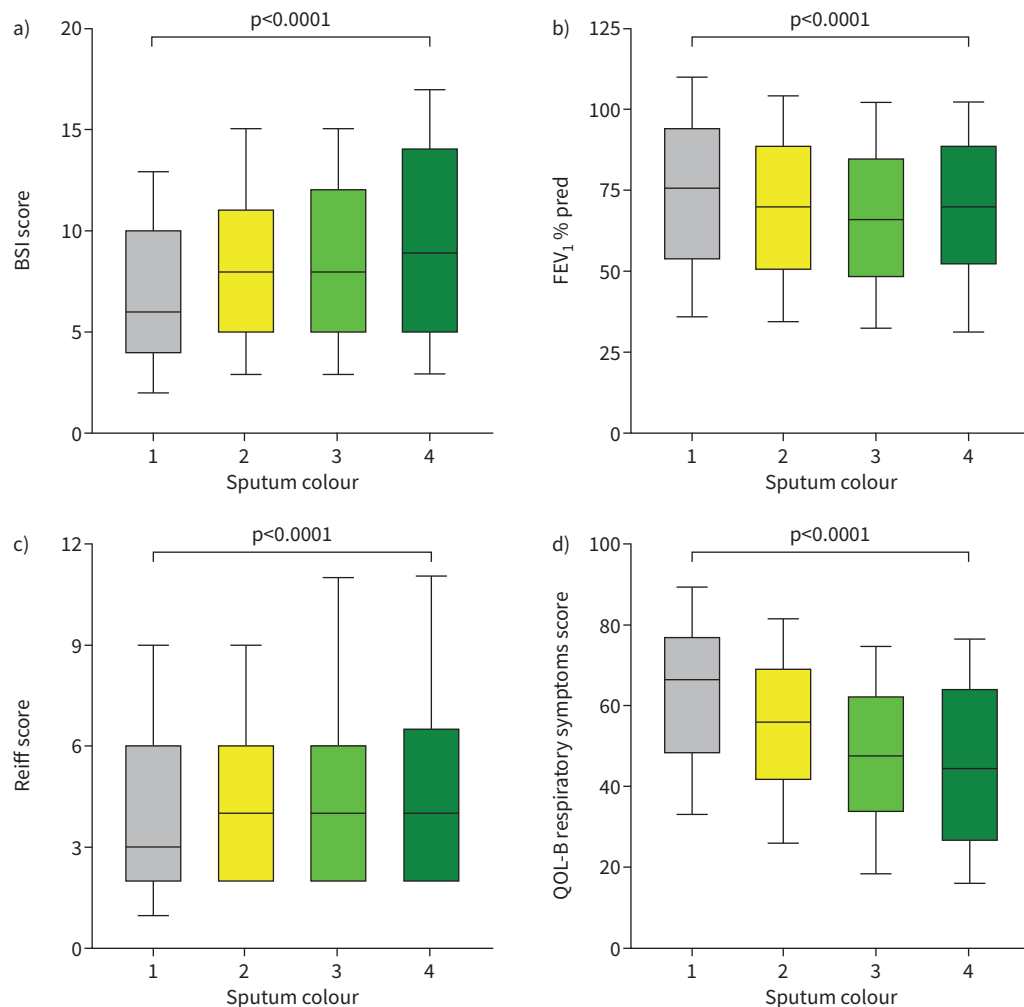


FIGURE 3 Disease severity and its relationship with sputum colour: **a)** bronchiectasis severity index (BSI) score, **b)** forced expiratory volume in 1 s (FEV₁) percentage predicted, **c)** Reiff score and **d)** Quality of Life Questionnaire-Bronchiectasis (QOL-B) respiratory symptoms score. Sputum colour is graded as 1=mucoid, 2=mucopurulent, 3=purulent and 4=severely purulent. Box plots show median and interquartile range with whiskers at the 10–90th percentiles.

Sputum colour was strongly associated with the risk of future exacerbations. Compared to patients with mucoid sputum (reference group), patients with mucopurulent sputum experienced significantly more exacerbations (incident rate ratio (IRR) 1.29, 95% CI 1.22–1.38; $p < 0.0001$), while the rates were even higher for patients with purulent sputum (IRR 1.55, 95% CI 1.44–1.67; $p < 0.0001$) and severely purulent sputum (IRR 1.91, 95% CI 1.52–2.39; $p < 0.0001$) (figure 5b). The relationship between sputum colour and exacerbations was evaluated in subgroups of patients based on disease severity using the BSI, *P. aeruginosa* infection status, baseline FEV₁ and prior exacerbation history, showing clear associations between increasing sputum purulence and increasing exacerbations independent on these other criteria (supplementary table S4).

For hospitalisation, increasing sputum colour was also associated with worse clinical outcomes with rate ratios (compared to patients with mucoid sputum) of 1.41 (95% CI 1.29–1.56; $p < 0.0001$), 1.98 (95% CI 1.77–2.21; $p < 0.0001$) and 3.05 (95% CI 2.25–4.14; $p < 0.0001$) for patients with mucopurulent, purulent and severely purulent sputum, respectively (figure 5b).

We performed a number of sensitivity analyses. Sputum colour remained strongly associated with future exacerbations even after adjustment for prior exacerbations. Compared to the reference group (mucoid sputum) the adjusted rate ratios for exacerbation frequency were 1.21 (95% CI 1.14–1.29), 1.31 (95% CI

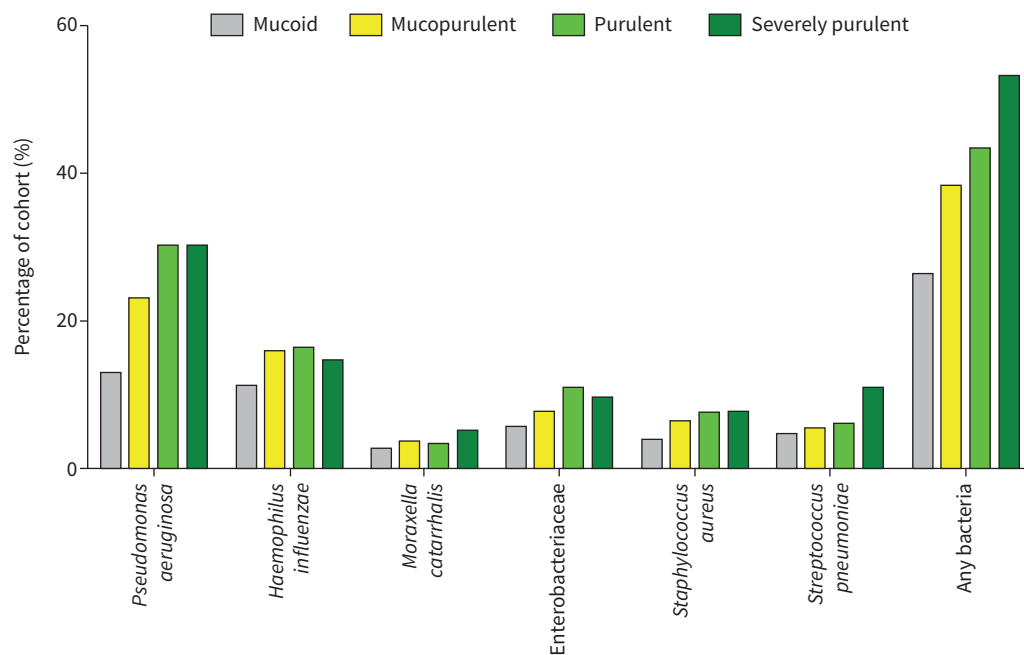


FIGURE 4 Percentage of all patients with positive sputum cultures for selected respiratory pathogens or any bacteria at baseline.

1.21–1.42) and 1.68 (95% CI 1.33–2.11) for mucopurulent, purulent and severely purulent sputum, respectively. Sputum colour was also clearly associated with future exacerbation risk in patients using long-term macrolide or inhaled antibiotics at baseline (supplementary table S4). Since *P. aeruginosa* is a strong predictor of future hospitalisation and sputum purulence was strongly associated with *P. aeruginosa* infection, an analysis was conducted adjusting for *P. aeruginosa* in the negative binomial model. This shows rate ratios of 1.20 (95% CI 1.10–1.30), 1.53 (95% CI 1.39–1.68) and 1.74 (95% CI 1.33–2.29) for mucopurulent, purulent and severely purulent sputum, respectively. In an additional analysis, sputum colour was also associated with a shorter time to the first severe exacerbation following baseline (supplementary table S5).

There were 582 deaths during follow-up. Mortality was significantly increased with increasing sputum purulence (hazard ratio 1.12, 95% CI 1.01–1.24; $p=0.027$), indicating a 12% increased risk of death for each 1-point increase in sputum purulence. For patients with purulent sputum at baseline compared to patients with muroid sputum the corresponding hazard ratios were 1.02 (95% CI 0.85–1.23) for mucopurulent sputum, 1.26 (95% CI 1.01–1.57; $p=0.039$) for purulent sputum and 1.60 (95% CI 0.90–2.86; $p=0.11$) for severely purulent sputum. The Kaplan–Meier survival curve is shown in figure 5c.

Visit-to-visit repeatability of sputum colour

7632 patients were included in the analysis of repeated sputum colour assessment over time, on the basis of having at least two assessments 12 months apart. Sputum colour showed a degree of stability from visit to visit in the stable state within individuals. We analysed the levels of agreement between baseline and year 1 sputum colour assessments within individuals. Of those with muroid sputum at baseline, 89.3% of patients had muroid sputum at their next follow-up visit. The corresponding figures were 88.2% for mucopurulent sputum at both visits, 78.6% for purulent sputum and 79.7% for severely purulent sputum. The Sankey diagram is shown in supplementary figure S2.

Discussion

Bronchiectasis is a chronic inflammatory disorder [10]. Airway inflammation in bronchiectasis is a key component of the vicious vortex of disease and is believed to play a key role in disease progression [21]. Sputum colour represents a potentially clinically useful, simple and non-invasive marker of airway inflammation [9, 10]. Our study shows that sputum colour as determined by a validated sputum colour chart is strongly associated with disease severity measured by the BSI, lower FEV₁, worse quality of life and greater radiological severity. Patients with purulent sputum are more likely to have positive sputum

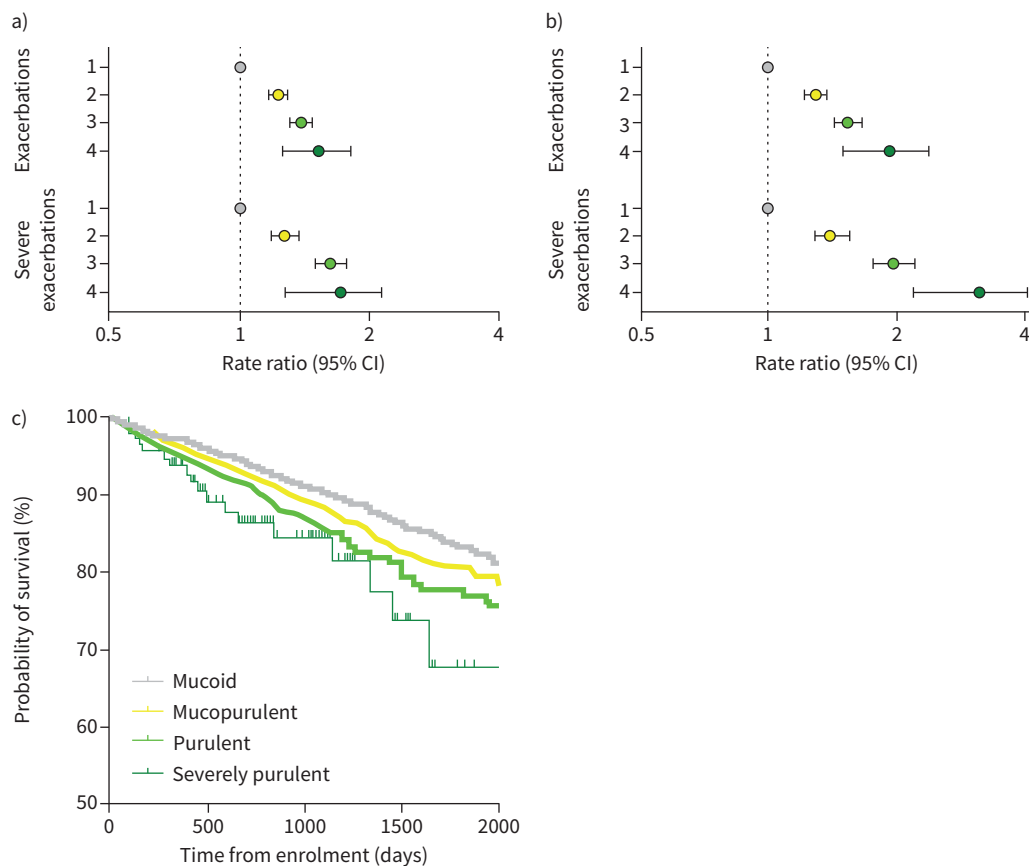


FIGURE 5 a, b) Forest plots of the frequency of exacerbations and severe exacerbations across the four sputum colour groups (1=muroid sputum (reference group), 2=mucopurulent sputum, 3=purulent sputum and 4=severely purulent sputum): a) in the previous year and b) during follow-up. c) Kaplan–Meier survival curve.

cultures for multiple bacteria and particularly *P. aeruginosa*, an organism that is known to be associated with greater risk of hospitalisation, mortality and FEV₁ decline [22]. Patients with greater sputum purulence experience more frequent exacerbations and a higher risk of severe exacerbations during follow-up. Importantly, this increased risk is seen even when patients are matched for severity of disease or prior exacerbation history. When we examined subgroups of patients defined by their prior exacerbation history (0, 1, 2 or ≥ 3 exacerbations in the previous year), patients with more purulent sputum still experienced more exacerbations. Similar results were observed for severe exacerbation risk. Finally, survival was also lower for patients with increased sputum purulence. Taken together our results suggest that sputum purulence can be used as a relatively simple risk stratification tool in clinical practice to identify patients at greater risk of severe disease, positive sputum cultures and future exacerbations.

Our study is observational and it cannot prove that any of these relationships are causal. It is unlikely that the presence of purulent sputum, in itself, is causing any of these poor outcomes. It is most likely that purulent sputum is a reflection of underlying lung inflammation and that this inflammation directly contributes to lung injury, while the resulting exacerbations contribute to disease progression [12, 23]. Sputum colour therefore represents a potentially clinically useful and non-invasive marker of airway inflammation.

Previous work has shown that sputum purulence reflects the presence of neutrophilic inflammation [11, 12]. MPO, an enzyme contained within the azurophilic granules of neutrophils, is responsible for the green colour in purulent sputum. MPO itself generates the toxic metabolite hypochlorite which contributes to oxidative stress and inflammation in the airways [24]. MPO is a key component of neutrophil extracellular traps (NETs) which are believed to be the dominant mechanism of neutrophilic inflammation in the bronchiectasis airway and which have also been linked with disease severity and future risk of exacerbations [12, 25]. NETs release multiple granule and cytoplasmic proteins associated with DNA and

histones which together amplify lung inflammation and protease-mediated degradation of lung tissue [12]. Neutrophil elastase, which has been strongly linked to disease progression in bronchiectasis, is released from the same granules as MPO and increases with increasing sputum purulence [3, 8]. The relationships between neutrophilic inflammation and exacerbations and survival seen in this study mirror those seen with laboratory assays of neutrophilic inflammation such as elastase and NETs, and confirm, in a much larger cohort, that neutrophilic inflammation is a key prognostic marker in bronchiectasis.

Recognition that bronchiectasis is an inflammatory disease has led to the development of novel anti-inflammatory treatment strategies including dipeptidyl peptidase-1 inhibition, a treatment that reduces neutrophilic inflammation by blocking neutrophil serine protease activation in the bone marrow [26]. This was shown to prolong the time to first exacerbation in a phase 2 trial [26]. A phase 3 trial is ongoing. In that trial, sputum purulence was used as an inclusion criteria in an effort to enrol patients with significant neutrophilic inflammation and a higher risk of exacerbations. Our data would support that sputum colour can be used as such a marker for trials and may in future be useful to identify patients for anti-inflammatory treatment.

There is a strong relationship between sputum purulence and airway infection, which is the major driver of neutrophil recruitment to the airway, and this was clearly shown in our data where positive sputum cultures greatly increased as sputum purulence increased. Given this relationship, sputum purulence may be a promising biomarker to identify patients that would respond to antibiotic treatment. In an analysis of the AIR-BX trials of inhaled aztreonam, sputum purulence was significantly reduced during the on-cycles of treatment [27]. More importantly, patients with purulent sputum (identified on self-reported questionnaire) had a significant improvement in quality of life on treatment, while patients without sputum purulence did not [27]. Conversely, patients without sputum purulence had a significantly increased frequency of exacerbations and adverse events with inhaled antibiotic treatment [27]. This suggests that antibiotic treatment is most likely to be effective in patients with higher levels of neutrophilic inflammation and bacterial load, a concept now supported by several studies in bronchiectasis [28–31].

Sputum colour identifies patients at increased risk but it is clear from our data that patients with mucoid sputum can still experience exacerbations, including severe exacerbations, and may have severe bronchiectasis. It is increasingly recognised that bronchiectasis is a heterogeneous disease with multiple endotypes [21]. Endotyping of this subgroup of patients without clear neutrophilic inflammation is important. Recent data suggest around 20% of bronchiectasis patients without asthma have eosinophilic inflammation, which would not be expected to produce sputum purulence and may therefore explain some of the burden of disease in the subgroup [28, 32–34]. Other treatable traits are likely to be identified in this subgroup through ongoing research into inflammatory endotypes [35].

Our study has unique strengths, including the very large sample size, systematic collection of data and inclusion of a large number of countries. Limitations of this analysis include the real-life nature of the data collection. Although the sputum colour chart was provided to all sites through the online data collection system, monitoring how this was used across so many sites is not feasible and variation in practice is inevitable. Sputum characteristics may vary by time of day, or depending on airway clearance techniques or other interventions [36]. Sputum cultures were not mandatory and so the analysis of sputum bacteria is limited by whether or not patients had sputum cultures performed for clinical reasons. The frequency of bacteria in our study therefore likely underestimates the true prevalence of pathogens. Other sputum parameters such as plugging on CT and rheology parameters such as viscosity may provide additional information but were not evaluated in this study.

In summary we show that sputum colour is a clinically useful non-invasive inflammatory biomarker that is associated with disease severity and identifies patients at risk of future exacerbations.

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