Telomere length in circulating leukocytes is associated with lung function and disease

Albrecht, Eva; Sillanpää, Elina; Karrasch, Stefan; Alves, Alexessander Couto; Codd, Veryan; Hovatta, Iliris; Buxton, Jessica L; Nelson, Christopher P; Broer, Linda; Hägg, Sara; Mangino, Massimo; Willemsen, Gonneke; Surakka, Ida; Ferreira, Manuel AR; Amin, Najaf; Oostra, Ben A; Bäckman, Heli M; Peltonen, Markku; Sarna, Seppo; Rantanen, Taina; Sipilä, Sarianna; Korhonen, Tellervo; Madden, Pamela AF; Gieger, Christian; Höpp, Rudolf A; Heinereich, Joachim; Daha, Ilmar; Hübner, Rudolf M; Botter; Blakemore, Alexandra IF; Geus, Eco JC de; Nyholt, Dale R; Henders, Anjali K; Piirilä, Päivi L; Rissanen, Aila; Magnusson, Patrik KE; Viñuela, Ana; Pietiläinen, Kirsi H; Martin, Nicholas G; Pedersen, Nancy L; Boomsma, Dorret I; Spector, Tim D; Duijn, Cornelia M; Kaprio, Jaakko; Samani, Nilesh J; Jarvelin, Marjo-Riitta; Schulz, Holger

doi:10.1183/09031936.00046213

All material supplied via JYX is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.
Telomere Length in Circulating Leukocytes Is Associated with Lung Function and Disease


1. Institute of Genetic Epidemiology, Helmholtz Zentrum München - German Research Center for Environmental Health, Neuherberg, Germany.
2. Gerontology Research Center and Department of Health Sciences, University of Jyväskylä, Finland.
3. Institute and Outpatient Clinic for Occupational, Social and Environmental Medicine, Ludwig-Maximilians-Universität, Munich, Germany.
4. Institute of General Practice, University Hospital Klinikum rechts der Isar, Technische Universität München, Munich, Germany.
5. Institute of Epidemiology I, Helmholtz Zentrum München - German Research Center for Environmental Health, Neuherberg, Germany.
6. Dept of Epidemiology and Biostatistics, MRC-HPA (Health Protection Agency) Centre for Environment and Health, School of Public Health, Faculty of Medicine, Imperial College London, UK.
7. Department of Cardiovascular Sciences, University of Leicester, Leicester, UK.
8. Leicester NIHR Biomedical Research Unit in Cardiovascular Disease, Glenfield Hospital, Leicester, UK.
10. Department of Biosciences, Viikki Biocentre, University of Helsinki, Finland.
11. Section of Investigative Medicine, Department of Medicine, Imperial College London, UK.
12. Netherlands Consortium for Healthy Aging, Leiden University Medical Center, Leiden, the Netherlands.
13. Department of Epidemiology, Erasmus Medical Center, Rotterdam, the Netherlands.
14. Department of Medical Epidemiology and Biostatistics, Karolinska Institutet, Stockholm, Sweden.
15. Department of Medical Sciences, Molecular Epidemiology and Science for Life Laboratory, Uppsala University, Uppsala, Sweden.
16. Department of Twin Research and Genetic Epidemiology, King's College London, London, UK.
17. Dept of Biological Psychology, VU University Amsterdam, Amsterdam, the Netherlands.
18. Public Health Genomics Unit, Department of Chronic Disease Prevention, National Institute for Health and Welfare, Helsinki, Finland.
19. Institute for Molecular Medicine Finland FIMM, University of Helsinki, Finland.
20. Queensland Institute of Medical Research, Brisbane, Queensland, Australia.
22. Health and Social Welfare Department, City of Vantaa, Finland.
23. Department of Chronic Disease Prevention, National Institute for Health and Welfare, Helsinki, Finland.
24. Washington University School of Medicine, Saint Louis, USA.
25. Comprehensive Pneumology Center Munich (CPC-M), Member of the German Center for Lung Research, Munich, Germany.
26. Department of Internal Medicine V, University of Munich, Munich, Germany.
27. Thoracic Oncology Centre Munich, University of Munich, Munich, Germany.
28. Research Unit of Molecular Epidemiology, Helmholtz Zentrum München - German Research Center for Environmental Health, Neuherberg, Germany.
29. Munich Heart Alliance, Munich, Germany.
30. Institute of Epidemiology II, Helmholtz Zentrum München - German Research Center for Environmental Health, Neuherberg, Germany.
31. Institute of Medical Informatics, Biometry and Epidemiology, Chair of Genetic Epidemiology, Ludwig-Maximilians-Universität, Munich, Germany.
32. Klinikum Grosshadern, Munich, Germany.
33. Institute of Medical Informatics, Biometry and Epidemiology, Chair of Epidemiology, Ludwig-Maximilians-Universität, Munich, Germany.
34. Unit of Clinical Physiology, HUS Medical Imaging Center, Helsinki University Hospital, Helsinki Finland.
35. Obesity Research Unit, Department of Psychiatry, Helsinki University Central Hospital, Finland.
36. Obesity Research Unit, Department of Medicine, Division of Endocrinology, Helsinki University Central Hospital and University of Helsinki, Finland.
37. Institute of Health Sciences, University of Oulu, Finland
38. Unit of General Practice, University Hospital Oulu, Finland.
39. Biocenter Oulu, University of Oulu, Finland.
40. Department of Lifecourse and Services, National Institute for Health and Welfare, Oulu, Finland.

*These authors contributed equally to this work.

**Corresponding author:**
Holger Schulz, Prof. Dr. med
Helmholtz Zentrum München, German Research Center for Environmental Health
Institute of Epidemiology I
Ingolstädter Landstraße 1
85764 Neuherberg
Germany
Phone: +49 89 3187 4119
Fax: +49 89 3187 3380
schulz@helmholtz-muenchen.de

**Take home message (130 characters)**
Premature aging is involved in the pathobiology of COPD and asthma.
Lung function partially reflects biological aging due to intrinsic processes.


Abstract

Several clinical studies suggest the involvement of premature aging processes in COPD. Using an epidemiological approach we studied whether accelerated aging indicated by telomere length, a marker of biological age, is associated with COPD and asthma, and whether intrinsic age-related processes contribute to the inter-individual variability of lung function.

Our meta-analysis of 14 studies included 934 COPD cases with 15,846 controls defined according to GLI criteria (or 1,189 COPD cases according to GOLD), 2,834 asthma cases with 28,195 controls, and spirometric parameters (FEV\textsubscript{1}, FVC and FEV\textsubscript{1}/FVC) of 12,595 individuals. Associations with telomere length were tested by linear regression, adjusting for age, sex, and smoking status.

We observed negative associations between telomere length and COPD being stronger for COPD defined by GLI than GOLD (\(\beta=-0.0982, p=0.001\) vs. \(\beta=-0.0676, p=0.018\)) as well as asthma (\(\beta=-0.0452, p=0.024\)), with stronger effects in women compared to men. The investigation of spirometric indices showed positive associations between telomere length and FEV\textsubscript{1} (\(p=1.07\times10^{-7}\)), FVC (\(p=2.07\times10^{-5}\)), and their ratio FEV\textsubscript{1}/FVC (\(p=5.27\times10^{-3}\)). The effect was somewhat weaker in apparently healthy subjects compared to COPD or asthma patients.

Our results provide indirect evidence for the hypothesis that cellular senescence may contribute to the pathogenesis of COPD and asthma and that lung function may reflect biological aging primarily due to intrinsic processes which are likely to be aggravated in lung diseases.

Key words: biological age, premature aging, COPD, asthma, spirometry
**Introduction**

An increasing life expectancy is associated with an increased susceptibility for prevailing chronic diseases, such as cardiovascular and neurological diseases, type 2 diabetes and cancer, suggesting that common, age-related processes are involved in these diseases [1-4]. The lung is known to undergo age-related processes associated with a continuous decline in lung function [5, 6]. Chronic obstructive pulmonary disease (COPD), lung cancer and idiopathic pulmonary fibrosis are lung diseases with an increase in incidence by age. In COPD, chronic inflammation and oxidative stress are among the generally accepted pathophysiological mechanisms but, as discussed for other degenerative diseases, accelerated aging resulting in premature cell senescence may contribute to the pathobiology [7-9]. Although clinical and epidemiological studies provide some evidence for this hypothesis the data base is still limited [8] so that our study aims to provide further clues on this.

Telomeres made up of the simple repetitive sequence TTAGGG in humans [10] are specialized DNA structures which in concert with telomere specific proteins protect the ends of chromosomes and maintain the integrity of the genome [3]. They progressively shorten with each cell division [11] and after reaching a critical length, either cellular senescence or apoptosis is induced [3]. Telomeres are therefore considered as a marker of biological age. Their length is affected by various factors, such as chronic inflammation or oxidative stress [3], but has also been shown to have a heritable component [12]. Recent data suggest that shorter telomere length is associated with an increased risk of total and cancer mortality in COPD patients [13]. Shortened telomeres were found in pulmonary vascular endothelial cells, alveolar epithelial cells and circulating leukocytes of COPD patients [14-18] supporting the notion of accelerated aging in COPD. Rode et al. [18] reported multivariable-adjusted odds ratios of 1.15 (95% CI 1.06 to 1.25) for shortest versus longest telomere quartiles for COPD.

Smoking, a major cause of COPD, is associated with different signs of premature aging which
is particularly obvious in the skin [8] suggesting that environmental exposure may play an
important role in triggering processes related to biological aging.

Since the lung is continuously exposed to environmental hazards, lung function per se may be
a surrogate marker for biological age in light of the large inter-individual variability observed
[19]. Only a few case-control studies [14, 20] have investigated the relationship between
telomere length and spirometric indices. One large population based study was recently
published by Rode et al. [18] reporting a modest correlation between telomere length and lung
function in terms of the spirometric indices forced expiratory volume in one second (FEV\textsubscript{1}),
forced vital capacity (FVC) and their ratio FEV\textsubscript{1}/FVC.

In a meta-analysis of 14 European studies embedded in the ENGAGE consortium, we studied
the relationship between telomere length, lung function and lung disease to address the
question whether accelerated aging indicated by telomere length may be involved in the
pathogenesis of COPD and asthma, and whether intrinsic age-related processes may
contribute to the inter-individual variability of lung function. For this purpose, we explored
the association between circulating leukocyte telomere length and COPD or asthma. Although
these are different obstructive disease entities, they share chronic inflammation as a hallmark
of disease which may result in accelerated aging and telomere shortening. We further
investigated the association between telomere length and lung function using the spirometric
indices FEV\textsubscript{1}, FVC and FEV\textsubscript{1}/FVC.

Methods

Study populations

This meta-analysis comprises data from 14 European studies, with details provided in the
Online Data Supplement. In the analysis of telomere length and COPD, we combined data
of nine studies (EX-ATHLETES, FITSA, KORA Age, KORA F3, KORA F4, NAG-FIN, NFBC1966, TwinGene, and TwinsUK), totaling 934 cases and 15,846 controls (Table 1). COPD was defined as z(FEV₁/FVC) < -1.6445 (5% lower limit of normal (LLN) according to the Global Lung Function Initiative (GLI) [19]) if spirometry was available (see below), or based on physician diagnosis otherwise. In a sensitivity analysis we replaced the GLI criteria by the GOLD criteria (FEV₁/FVC<0.70) [21] to define COPD. The analysis of telomere length in asthma comprised 13 studies (ERF, EX-ATHLETES, FITSA, GRAPHIC, KORA Age, KORA F3, KORA F4, NAG-FIN, NFBC1966, NTR, QIMR, TwinGene, and TwinsUK), with 2,834 cases and 28,195 controls (Table 2). Asthma was defined by physician diagnosis or self-reports in questionnaires or by asthma-specific medication intake. Spirometric measurements (FEV₁, FVC and FEV₁/FVC) were available for 12,595 individuals from seven studies (FITSA, KORA Age, KORA F3, KORA F4, NFBC1966, TwinFat, and TwinsUK). Spirometry had been performed in line with international standards [22, 23]. Relative telomere length was determined by qPCR [24] in all studies. Measurement details by study are provided in the Online Data Supplement. The local ethic committees had approved all studies and all participants had given their written informed consent.

Statistical analysis

Associations of telomere length with COPD, asthma, FEV₁, FVC and FEV₁/FVC were tested by linear regression models with telomere length as outcome in all models. To account for heterogeneity between studies, telomere length was standardized within each study prior to the analysis, using a z-transformation after initially adjusting for age and sex, i.e. scaling the residuals of the regression of telomere length on age and sex to zero mean and unit variance. COPD and asthma cases, respectively, were coded "1", whereas controls were coded "0". Also the spirometric indices were transformed to z-scores taking into account age, height, and gender of each individual. Therefore Global Lung Function Initiative (GLI) reference
equations for spirometry [19] were applied to calculate z-scores for FEV$_1$, FVC, and FEV$_1$/FVC from skewness (L), the coefficient of variation (S) and the predicted value (M) according to the LMS-equations by using the provided software (http://www.lungfunction.org/tools).

Within the linear regression model we adjusted for ever and current smoking, as well as for study specific covariates as case/control status or family structure if appropriate. As both, telomere length and lung function measurements were already adjusted for age and sex, the association model itself did not contain these covariates. All analyses were primarily conducted in all available study samples and additionally conducted stratified by sex. The z-transformation of telomere length was performed in males and females separately for the sex-stratified analysis. For the analyses of FEV$_1$, FVC, and FEV$_1$/FVC, we additionally stratified into the subgroups “apparently lung healthy”, “COPD cases” and “asthmatics”.

The group of apparently lung healthy subjects was determined by exclusion of all subjects with a history of asthma, COPD, or other reported respiratory diseases, and all subjects with a reported acute respiratory tract infections within the last three weeks. The group was further divided into “current/former” and “never” smokers. In the group of healthy smokers we further investigated subjects showing the lower and upper 25%-quantiles of lung function (FEV$_1$, FVC or FEV$_1$/FVC respectively). The single study results were combined in a meta-analysis with inverse variance weighting, performed in the statistical software R (http://www.r-project.org) using the meta-package with fixed and random effects. As a measure for heterogeneity, I$^2$ values were calculated [25] and Cochran’s heterogeneity test was performed. As a sensitivity analysis in COPD, we excluded first all subjects over 70 years and then all subjects over 60 years from the analysis.

Results

**COPD**
By combining nine studies including 934 COPD cases and 15,846 controls according to GLI (Table 1), we observed a significant negative association between COPD and telomere length ($\beta$=-0.0982, $p=0.001$ with fixed effects; $\beta$=-0.0953, $p=0.012$ with random effects, $I^2=27.7\%$, $p_{het}=0.198$). With COPD defined by GOLD criteria there were more COPD cases ($n=1,189$) with an increase in older and a reduction in younger subjects. The association with telomere length using GOLD criteria was now more heterogeneous across studies and less significant ($\beta$=-0.0676, $p=0.018$ with fixed effects). Figure 1 shows study specific and combined effect estimates of a fixed and random effects model with COPD defined by GLI. The association was strong in the female subsample ($n=10,435$; $\beta$=-0.1306, $p=3.6\times10^{-4}$ with fixed effects; $\beta$=-0.1312, $p=6.7\times10^{-4}$ with random effects; $I^2=5.8\%$, $p_{het}=0.385$) whereas in the male subsample no significant relationship was detectable ($n=6,354$; $\beta$=-0.0242, $p=0.663$ with fixed effects; $\beta$=-0.0329, $p=0.622$ with random effects; $I^2=23.5\%$, $p_{het}=0.250$). Figure E1 shows the meta-analysis stratified for sex. The two studies showing positive effect estimates, EX-ATHLETES and NAG-FIN, are selective in their study design: NAG-FIN comprises families of ever heavy smokers, and the EX-ATHLETES are former male top athletes with matched controls and a mean age of 72.7 years. Since COPD shows an age-related increase in incidence, we conducted sensitivity analyses to investigate whether the observed association is affected by age. Exclusion of subjects $>70$ years or $>60$ years showed no significant differences for the effect estimates in subgroups of both sexes (Figure E2), confirming that the association is not driven by older age groups.

**Asthma**

By combining 13 studies with 2,834 asthma cases and 28,195 controls (Table 2, Figure 2), we observed a negative association between telomere length and asthma. This was significant in a fixed effects model ($\beta$=-0.0452, $p=0.024$) and suggestive in a random effects model ($\beta$=-0.0446, $p=0.093$; $I^2=30.4\%$, $p_{het}=0.141$). The effect was driven by the female subsample
(n=18,776, β=-0.0716, p=0.003 with fixed effects; β =-0.0745, p=0.008 with random effects; I²=14.9%, phet=0.298) and not seen in the male subsample (n=12,253; β=0.0110, p=0.751 with fixed effects; β=0.0026, p=0.960 with random effects; I²=44.9%, phet=0.052; Figure E3).

*Lung function*

By combining data of seven studies, totaling 12,595 individuals (Table 3, Figure 3), we observed highly significant positive associations between telomere length and spirometric indices measured as FEV₁ (β=0.0455, p=1.07x10⁻⁷ with fixed and random effects; I²=0%), FVC (β=0.0401, p=2.07x10⁻⁵ with fixed and random effects; I²=0%), and their ratio FEV₁/FVC (β=0.0238, p=5.27x10⁻³ with fixed and random effects; I²=0%). The effect for FEV₁ was higher in women compared to men (β=0.0548 versus β=0.286 with random effects). The meta-analysis stratified by sex is shown in Figure E4.

Figure 4 shows the association results stratified by lung health status. Compared to “healthy”, we found somewhat stronger effects in the disease subgroups of COPD and asthma cases. A comparison of the effect estimates stratified by health status as well as by sex is presented in Figure E5. The stronger effects found in COPD were predominantly seen in men and less obvious in women. The opposite was observed for asthma, where the effects were strong in women. With regard to smoking, within the healthy subgroups, the observed effects were stronger in “healthy never smokers” compared to “healthy ever smokers” for FEV₁ and FVC (see Figure E6). To further explore the contribution of smoking we stratified the group of healthy smokers (current or ex) by lung function status (lower 25% or upper 25% within this subgroup). The results suggest that there was no difference between those two groups for FEV₁. In FVC, an effect was only seen in individuals with poor lung function (lower 25%). Although differences between subgroups were noticeable, they did not differ significantly.
**Discussion**

We conducted a large study investigating the relationship between telomere length and lung function and disease, assessed in multiple European cohorts unselected for lung disease. We found highly significant positive associations between telomere length from peripheral leukocytes and spirometric indices measured as FEV$_1$, FVC, and FEV$_1$/FVC in a meta-analysis of seven studies with 12,595 individuals. When stratifying by lung health status, larger effects were seen in the subgroups of COPD patients or asthmatics. This suggests that lung function decline in part reflects biological aging due to intrinsic processes which are likely to be aggravated in asthma or COPD due to mechanisms promoting cell senescence.

Tobacco smoke is a well-known environmental factor which promotes aging processes and cellular senescence [8]. The recent large, population-based study by Rode et al. (2013) [18] revealed that having ever smoked and the cumulative pack-years smoked were associated with telomere length in 46,396 adults. This is in line with previous population-based findings [26]. However, in clinical studies these effects were not seen [14, 17, 20]. When stratifying by smoking status, we observed no evident associations between telomere length and lung function indices in ever smokers. Also stratifying by lung function within the group of healthy smokers (current and ex) did not clarify the issue, although for FVC an effect could be detected in smokers of the lower quartile. The underlying reason for detecting no effect may be found in the complex interactions between smoking and genetic and/or life style factors, such as antioxidant diet or physical activity, affecting biological age and its markers [1, 3, 27-32], but also in the heterogeneity of smoking exposures, its amount and duration.

Up to now, a limited number of studies have addressed the association between lung function and telomere length. Mui et al. (2009) [20] observed a positive association in a sample of
COPD patients, and Tsuji et al. (2006) [16] reported that airflow limitation and alveolar cell senescence were positively correlated with each other. Other studies failed to find significant associations between spirometric parameters and telomere length [14, 17, 33], although one study found that parameters of gas exchange (arterial oxygen and carbon dioxide pressures) were associated with telomere length in COPD patients [14]. The large population-based study by Rode et al. (2013) found weak but statistical significant positive correlations between telomere length and spirometric indices, which is confirmed by our results. Furthermore we observed the effects to be somewhat stronger in COPD or asthma patients compared to healthy individuals, suggesting that intrinsic age-related processes may be aggravated by chronic inflammatory processes occurring either locally in the lung or systemically.

In both, COPD and asthma patients, we observed shorter telomeres compared to healthy controls. In COPD, the association was stronger when defining cases by the age dependent lower limit of normal for FEV\textsubscript{1}/FVC according to GLI [19] compared to the fixed cut off of 0.70 given by GOLD [21]. This suggests that the GLI approach better suits the transition from health to disease. In both diseases, effect estimates appeared to be larger in females than in males although sex differences were not statistically significant. With respect to COPD, this might be consistent with the observation that females appear to be more susceptible to COPD than males [34] but the causality certainly needs to be proved. Whereas our findings for asthma are novel, the results for COPD are in line with previous findings in case-control [14-17] and population-based studies [18]. This suggests that, as already shown for other chronic diseases [1, 3, 35], accelerated aging may contribute to the pathogenesis of asthma and COPD.
Our epidemiological finding is supported by results from clinical studies showing shorter telomeres in alveolar epithelial and endothelial cells from patients with emphysema [16]. Amsellem et al. reported a higher percentage of pulmonary vascular endothelial cells stained for senescence markers in COPD patients than in lung healthy controls [15]. This in line with senescent-type growth characteristics of lung fibroblasts [36]. Furthermore, cellular senescence of pulmonary smooth muscle cells appears to be involved in the pathogenesis of pulmonary hypertension in COPD [37]. Several mechanisms have been proposed for abnormal aging in COPD including chronic inflammation, oxidative stress, mitochondrial dysfunction, altered energy metabolism, abnormal regulation of aging processes, cellular and immunosenescence, and telomere dysfunction [3, 7-9, 15]. Analogous mechanisms in asthma have not been explored in detail but due to the inflammatory nature of both diseases some of the above mentioned factors are likely to also play a role in asthma. Possible consequences for both diseases are very difficult to predict but one might speculate that the aging processes may be reflected in the shorter life expectancy and an increased risk for cognitive impairment and dementia as reported for asthma and COPD [38-40].

The observed associations between telomere length and both diseases were not as strong as one might have initially expected, considering the large sample size included. In case of COPD, in the population-based approach of Rode et al. [18] also a much weaker association was observed than previous case-control studies had suggested [14]. In our case this may be related to the fact that mostly mild to moderate disease stages were included in the study samples. E.g. for COPD in the KORA cohorts GOLD stages I and II covered 94.3% of COPD cases. Rode et al. also observed weaker effects for stages I (OR=1.09, 95% CI 0.97 to 1.23) and II (OR=1.17, 1.04 to 1.31) compared to more advanced GOLD stages [18] after multiple adjustment. In the case of asthma, the weakness of association could be due to the different methods of ascertaining asthma cases or phenotypic heterogeneity.
Moreover, as in many other studies, telomere length has been measured in circulating leucocytes and not in the cells of the primarily affected organ, i.e. the lung. Studies addressing the comparability of telomere length between different tissues found strong correlations in healthy individuals, but somewhat blunted ones in disease [41-44]. We cannot rule out that this may be a factor which affects the association of telomere length with lung diseases. Leukocyte telomere length is a complex trait that is shaped by many factors including genetic, epigenetic, lifestyle and environmental determinants, and their complex interaction is hardly understood. In the present analysis we therefore adjusted only for well accepted determinants. Certainly, the population-based epidemiological nature of the studies included comes along with distinct limitations. Population-based samples typically only scarcely include severe cases of lung diseases but predominantly early disease stages, in which age-related mechanisms may not be as significant as in more advanced stages that are primarily included in clinical cohorts [14-17]. Furthermore, our study design did not allow taking into account the known heterogeneity of COPD and asthma phenotypes. These entities may have different impacts on telomere length or may trigger premature aging processes via telomere-independent mechanisms as reported for fibroblasts of patients with lung emphysema [45]. Unlike in clinical studies, diagnosis of COPD and asthma had to rely mainly on self-reported physician diagnosis which certainly adds some potential for misclassification error. On the other hand, we employed the recent GLI reference values [19] for COPD diagnosis wherever possible. Also confounding effects, such as smoking or medication, could not be accounted for in the same way as a matched case-control study design can.

As this analysis combines a number of studies which are heterogeneous in their design (see Online Data Supplement), we report results of random effects models in addition to the results based on fixed effects in order to account for this heterogeneity. Naturally, confidence
intervals are larger with random effects. While both models reach statistical significance in COPD, statistical significance was only reached with the fixed effects model for asthma. The observed effect point estimates, however, were comparable between the fixed and the random effects model, supporting the biological significance of our findings. In COPD, our sensitivity analysis did not show an age-dependency (Figure E2). Two studies showing positive effect estimates for COPD were selective in their study design; in case of the EX-ATHLETES the positive effect of life-time physical exercise on biological age may have played a role [3, 27, 46, 47].

Conclusions
We investigated the relationship of telomere length, as a marker of biological age, with lung function and respiratory disease. We found highly significant positive associations between telomere length and lung function. Furthermore, shorter telomeres were seen in patients with COPD and asthma cases compared to healthy controls. Our results provide indirect evidence for the hypothesis that premature aging is involved in the pathophysiology of COPD and asthma and that lung function partially reflects biological aging due to intrinsic processes. These processes are likely to be aggravated by lung diseases promoting cellular senescence, although the average effect seems to be not particularly strong.

Acknowledgments
A detailed list of acknowledgments is provided in the Online Data Supplement.
References


30. Yen YC, Lung FW. Older adults with higher income or marriage have longer telomeres. Age Ageing 2012.


Figure legends

Figure 1: Associations between telomere length and COPD

Forest Plot comparing effects between studies, and showing combined effects in a fixed effects model as well as in a random effects model. Sex-stratified results are based on random effects models. 95% confidence intervals are given for all estimates. COPD was defined by GLI criteria.

Figure 2: Association between telomere length and asthma

Forest Plot comparing effects between studies, and showing combined effects in a fixed effects model as well as in a random effects model. Sex-stratified results are based on random effects models. 95% confidence intervals are given for all estimates.

Figure 3: Telomere length is associated with FEV$_1$, FVC and (FEV$_1$/FVC)

Forest Plot comparing effects between studies, and showing combined effects in a fixed effects model as well as in a random effects model. Sex-stratified results are based on random effects models. 95% confidence intervals are given for all estimates.

Figure 4: Associations between telomere length and FEV$_1$, FVC and (FEV$_1$/FVC), stratified by health status.

Forest Plot showing effects in the overall sample as well as in “apparently lung healthy” individuals only, for asthmatics, and patients with COPD to test the impact of lung disease on the effect. Effects are based on random effects models. 95% confidence intervals are given for all estimates.
### Table 1: Study characteristics of studies in COPD analysis defined by GLI criteria

<table>
<thead>
<tr>
<th>Study</th>
<th>total sample size</th>
<th>number of COPD cases</th>
<th>number of women</th>
<th>Smoking status never/former/current</th>
<th>Age [years] mean (sd) overall</th>
<th>Age [years] mean (sd) in cases</th>
<th>Age [years] mean (sd) in controls</th>
<th>Age diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX-ATHLETES</td>
<td>577</td>
<td>43 (7.5%)</td>
<td>0 (0%)</td>
<td>361/177/39</td>
<td>72.68 (5.92)</td>
<td>74.63 (6.97)</td>
<td>72.52 (5.81)</td>
<td>2.11</td>
</tr>
<tr>
<td>FITSA</td>
<td>386</td>
<td>22 (5.7%)</td>
<td>386 (100%)</td>
<td>333/31/21</td>
<td>68.45 (3.38)</td>
<td>69.27 (3.60)</td>
<td>68.40 (3.36)</td>
<td>0.87</td>
</tr>
<tr>
<td>NAG-FIN</td>
<td>1,718</td>
<td>126 (7.3%)</td>
<td>782 (45.5%)</td>
<td>204/804/710</td>
<td>55.89 (7.63)</td>
<td>58.40 (9.40)</td>
<td>55.69 (7.44)</td>
<td>2.71</td>
</tr>
<tr>
<td>KORA Age</td>
<td>905</td>
<td>54 (6.0%)</td>
<td>451 (49.8%)</td>
<td>510/351/44</td>
<td>75.67 (6.34)</td>
<td>75.02 (6.28)</td>
<td>75.71 (6.35)</td>
<td>-0.69</td>
</tr>
<tr>
<td>KORA F3</td>
<td>875</td>
<td>36 (4.1%)</td>
<td>458 (52.3%)</td>
<td>377/260/238</td>
<td>44.45 (8.93)</td>
<td>44.11 (9.57)</td>
<td>44.46 (8.91)</td>
<td>-0.35</td>
</tr>
<tr>
<td>KORA F4</td>
<td>2,803</td>
<td>243 (8.7%)</td>
<td>1,480 (52.8%)</td>
<td>1,230/1,048/525</td>
<td>54.86 (12.84)</td>
<td>59.35 (12.73)</td>
<td>54.44 (12.77)</td>
<td>4.91</td>
</tr>
<tr>
<td>NFBC1966</td>
<td>4,984</td>
<td>147 (2.9%)</td>
<td>2,594 (52.0%)</td>
<td>2,479/592/1,913</td>
<td>31 (0.2)</td>
<td>31 (0.2)</td>
<td>31 (0.2)</td>
<td>0</td>
</tr>
<tr>
<td>TwinGene</td>
<td>597</td>
<td>52 (8.7%)</td>
<td>597 (100%)</td>
<td>358/239*</td>
<td>71.72 (5.89)</td>
<td>72.50 (5.31)</td>
<td>71.65 (5.95)</td>
<td>0.85</td>
</tr>
<tr>
<td>TwinsUK</td>
<td>3,935</td>
<td>211 (5.4%)</td>
<td>3,687 (93.7%)</td>
<td>2,760/743/432</td>
<td>51.17 (13.12)</td>
<td>53.34 (13.06)</td>
<td>51.02 (13.14)</td>
<td>2.32</td>
</tr>
<tr>
<td>total</td>
<td>16,780</td>
<td>934 (5.6%)</td>
<td>10,435 (62.2%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.71*</td>
</tr>
</tbody>
</table>

*for TwinGene the numbers correspond to current smoking no/yes. *mean age difference between cases and controls, weighted by total sample size.

### Table 2: Study characteristics of studies in asthma analysis
<table>
<thead>
<tr>
<th>Study</th>
<th>total sample size</th>
<th>number of asthma cases</th>
<th>number of women</th>
<th>Smoking status never/former/current</th>
<th>Age [years] mean (sd) overall</th>
<th>Age [years] mean (sd) in cases</th>
<th>Age [years] mean (sd) in controls</th>
<th>Age diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERF</td>
<td>2,580</td>
<td>41 (1.6%)</td>
<td>1,468 (56.9%)</td>
<td>981/691/908</td>
<td>49.80 (15.67)</td>
<td>51.14 (13.35)</td>
<td>49.78 (15.71)</td>
<td>1.36</td>
</tr>
<tr>
<td>EX-ATHLETES</td>
<td>577</td>
<td>44 (7.6%)</td>
<td>0 (0%)</td>
<td>361/177/39</td>
<td>72.68 (5.92)</td>
<td>73.23 (5.98)</td>
<td>72.63 (5.92)</td>
<td>0.60</td>
</tr>
<tr>
<td>FITSA</td>
<td>423</td>
<td>33 (7.8%)</td>
<td>423 (100%)</td>
<td>369/32/21</td>
<td>68.61 (3.41)</td>
<td>68.27 (3.48)</td>
<td>68.64 (3.41)</td>
<td>-0.37</td>
</tr>
<tr>
<td>NAG-FIN</td>
<td>1,718</td>
<td>97 (5.6%)</td>
<td>936 (54.5%)</td>
<td>204/804/710</td>
<td>55.89 (7.63)</td>
<td>59.72 (9.07)</td>
<td>55.67 (7.48)</td>
<td>4.05</td>
</tr>
<tr>
<td>GRAPHIC</td>
<td>2,007</td>
<td>76 (3.8%)</td>
<td>994 (49.5%)</td>
<td>1,109/491/407</td>
<td>39.31 (14.50)</td>
<td>37.09 (14.20)</td>
<td>39.38 (14.51)</td>
<td>-2.29</td>
</tr>
<tr>
<td>KORA Age</td>
<td>868</td>
<td>51 (5.9%)</td>
<td>435 (50.1%)</td>
<td>494/332/42</td>
<td>75.65 (6.34)</td>
<td>76.02 (6.10)</td>
<td>75.63 (6.36)</td>
<td>0.39</td>
</tr>
<tr>
<td>KORA F3</td>
<td>2,532</td>
<td>191 (7.5%)</td>
<td>1,212 (47.9%)</td>
<td>1,133/863/536</td>
<td>53.62 (10.8)</td>
<td>55.77 (9.85)</td>
<td>53.44 (10.86)</td>
<td>2.33</td>
</tr>
<tr>
<td>KORA F4</td>
<td>2,797</td>
<td>231 (8.3%)</td>
<td>1,477 (52.8%)</td>
<td>1,228/1,045/524</td>
<td>54.90 (12.85)</td>
<td>54.15 (12.75)</td>
<td>54.97 (12.85)</td>
<td>-0.82</td>
</tr>
<tr>
<td>NFBC1966</td>
<td>4,843</td>
<td>433 (8.9%)</td>
<td>2,516 (52.0%)</td>
<td>2,463/590/1,790</td>
<td>31 (0.2)</td>
<td>31 (0.2)</td>
<td>31 (0.2)</td>
<td>0</td>
</tr>
<tr>
<td>NTR</td>
<td>7,529</td>
<td>906 (12.0%)</td>
<td>4,688 (62.3%)</td>
<td>3,734/2,213/1,582</td>
<td>42.50 (15.29)</td>
<td>41.51 (14.80)</td>
<td>42.64 (15.35)</td>
<td>-1.13</td>
</tr>
<tr>
<td>QIMR</td>
<td>315</td>
<td>149 (47.3%)</td>
<td>161 (51.1%)</td>
<td>NA</td>
<td>20.94 (5.48)</td>
<td>20.60 (5.40)</td>
<td>21.25 (5.56)</td>
<td>-0.65</td>
</tr>
<tr>
<td>TwinGene</td>
<td>597</td>
<td>50 (8.4%)</td>
<td>597 (100%)</td>
<td>358/239*</td>
<td>71.72 (5.89)</td>
<td>71.69 (7.56)</td>
<td>71.73 (5.73)</td>
<td>-0.04</td>
</tr>
<tr>
<td>TwinsUK</td>
<td>4,243</td>
<td>531 (12.5%)</td>
<td>3,869 (91.2%)</td>
<td>3,003/784/456</td>
<td>51.07 (13.39)</td>
<td>49.09 (14.20)</td>
<td>51.37 (13.25)</td>
<td>-2.28</td>
</tr>
<tr>
<td>total</td>
<td>31,029</td>
<td>2,833 (9.1%)</td>
<td>18,622 (60.0%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.27#</td>
</tr>
</tbody>
</table>

*for TwinGene the numbers correspond to current smoking no/yes. 
#mean age difference between cases and controls, weighted by total sample size.
Table 3: Study characteristics of studies in lung function indices analysis

<table>
<thead>
<tr>
<th>Study</th>
<th>FITSA</th>
<th>KORA Age</th>
<th>KORA F3</th>
<th>KORA F4</th>
<th>NFBC1966</th>
<th>TwinFat</th>
<th>TwinsUK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>386</td>
<td>905</td>
<td>875</td>
<td>1,291</td>
<td>4,984</td>
<td>219</td>
<td>3,935</td>
</tr>
<tr>
<td>number of women</td>
<td>386 (100%)</td>
<td>451 (49.8%)</td>
<td>458 (52.3%)</td>
<td>691 (53.5%)</td>
<td>2,594 (52.0%)</td>
<td>101 (46.1%)</td>
<td>3,687 (93.7%)</td>
</tr>
<tr>
<td>Age [years] mean (sd)</td>
<td>68.45 (3.38)</td>
<td>75.67 (6.34)</td>
<td>44.45 (8.93)</td>
<td>51.62 (5.73)</td>
<td>31 (0.2)</td>
<td>27.60 (1.98)</td>
<td>51.17 (13.12)</td>
</tr>
<tr>
<td>FEV$_1$ [l] mean (sd)</td>
<td>2.20 (0.49)</td>
<td>2.49 (0.72)</td>
<td>3.56 (0.82)</td>
<td>3.34 (0.82)</td>
<td>3.95 (0.79)</td>
<td>4.03 (0.84)</td>
<td>2.74 (0.66)</td>
</tr>
<tr>
<td>FVC [l] mean (sd)</td>
<td>2.82 (0.59)</td>
<td>3.36 (0.93)</td>
<td>4.3 (1.02)</td>
<td>4.30 (1.01)</td>
<td>4.72 (0.99)</td>
<td>4.74 (1.12)*</td>
<td>3.41 (0.73)</td>
</tr>
<tr>
<td>FEV$_1$/FVC mean [%] (sd)</td>
<td>78.19 (8.29)</td>
<td>74.32 (8.42)</td>
<td>83.09 (7.08)</td>
<td>77.65 (6.16)</td>
<td>84.11 (6.43)</td>
<td>84.98 (6.07)*</td>
<td>80.42 (8.47)</td>
</tr>
<tr>
<td>zFEV$_1$ mean (sd)</td>
<td>0.19 (1.34)</td>
<td>0.35 (1.17)</td>
<td>0.17 (1.06)</td>
<td>0.21 (1.16)</td>
<td>0.21 (1.01)</td>
<td>-0.03 (1.09)</td>
<td>-0.09 (1.13)</td>
</tr>
<tr>
<td>zFVC mean (sd)</td>
<td>0.13 (1.19)</td>
<td>0.47 (1.01)</td>
<td>-0.06 (0.98)</td>
<td>0.33 (0.97)</td>
<td>0.11 (0.95)</td>
<td>-0.29 (1.04)*</td>
<td>-0.09 (0.98)</td>
</tr>
<tr>
<td>zFEV$_1$/FVC mean (sd)</td>
<td>-0.54 (1.13)</td>
<td>-0.26 (0.97)</td>
<td>0.42 (1.13)</td>
<td>-0.28 (0.89)</td>
<td>0.15 (1.13)</td>
<td>0.20 (0.96)*</td>
<td>-0.02 (1.12)</td>
</tr>
<tr>
<td>Smoking status</td>
<td>333/31/21</td>
<td>510/351/44</td>
<td>377/260/238</td>
<td>496/496/299</td>
<td>2,479/592/1,913</td>
<td>110/54/55</td>
<td>2,760/743/432</td>
</tr>
</tbody>
</table>

*In TwinFat the analysis of FVC and FEV$_1$/FVC is based on a subsample of n=124 subjects.