ORIGINAL ARTICLE

Ventilation heterogeneity in the acinar and conductive zones of the normal ageing lung

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ABSTRACT

Rationale Small airways function studies in lung disease have used three promising multiple breath washout (MBW) derived indices: indices of ventilation heterogeneity in the acinar (Sacrin) and conductive (Scond) lung zones, and the lung clearance index (LCI). Since peripheral lung structure is known to change with age, ventilation heterogeneity is expected to be affected too. However, the age dependence of the MBW indices of ventilation heterogeneity in the normal lung is unknown.

Objectives The authors systematically investigated Sacrin, Scond or LCI as a function of age, testing also the robustness of these relationships across two laboratories.

Methods MBW tests were performed by never-smokers (50% men) in the age range 25–65 years, with data gathered across two laboratories (n=120 and n=60). For comparison with the literature, the phase III slopes from classical single breath washout tests were also acquired in one group (n=120).

Measurements and main results All three MBW indices consistently increased with age, representing a steady worsening of ventilation heterogeneity in the age range 25–65. Age explained 7–16% of the variability in Sacrin and Scond and 36% of the variability in LCI. There was a small but significant gender difference only for Sacrin. Classical single breath washout phase III slopes also showed age dependencies, with gender effects depending on the normalisation method used.

Conclusions With respect to the clinical response, age is a small but consistent effect that needs to be factored in when using the MBW indices for the detection of small airways abnormality in disease.

INTRODUCTION

The multiple breath washout (MBW) test has been advocated for small airways detection in obstructive lung disease.1 2 Initially propelled by paediatric clinical lung research but now also promoted in adult lung disease, the most frequently reported MBW index is the lung clearance index (LCI).3–5 First introduced in 1951 as a measure of overall lung ventilation heterogeneity,6 LCI is currently deemed useful in the early detection of cystic fibrosis lung disease,5 with the specific advantages that LCI requires no particular breathing volumes and is quasi independent of lung growth (1–17 years).7 In adults, an analysis of the MBW phase III slope was proposed to distinguish ventilation heterogeneity generated in acinar air spaces from that originating in the more proximal lung.8 The two most relevant MBW-derived indices of ventilation heterogeneity are referred to as Sacrin (for ventilation heterogeneity generated peripheral to the acinar entrance) and Scond (for ventilation heterogeneity generated in the conductive lung zone). An exhaustive review of theory and experiments underpinning this phase III slope analysis are part of a recent update of the Handbook of Physiology,9 and the most critical aspects are iterated in the online supplement. Due to intrinsic structural heterogeneity of the airways within the lungs, Sacrin and Scond are non-zero in the normal lung, but show marked increases in lung disease.10–16 In patients with chronic obstructive pulmonary disease those with emphysema show a greater Sacrin,10 the extent of Sacrin increase is associated with carbon monoxide transfer factor,11 and with high-resolution CT lung density.12 In asthma, patients with an increased Scond are better responders to small particle-sized corticosteroids,13 and Sacrin correlates with an increased alveolar nitric oxide.14 In adult asthma, Scond is a predictor of airway hyperresponsiveness, independent of inflammation,15 and in preschool wheezers Scond is a sensitive indicator of abnormal pulmonary function.16

Key messages

What is the key question?

► It has been shown that alveolar architecture changes with age, however the age dependence of lung function indices that can actually measure functional change in the alveolar region have yet to be investigated.

What is the bottom line?

► If the alveolar architecture changes with age are large enough to be reflected functionally in small airway indices, these need to be acknowledged because early changes in the small airways may be a normal ageing effect.

Why read on?

► While previous studies clearly show clinical usefulness of indices that reflect gas mixing within the small airways, this study illustrates how neglecting the effect of age can unduly lead to diagnosis of small airway dysfunction in older people.

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To date, no comprehensive reports exist of LCI, \( S_{\text{acin}} \) and \( S_{\text{cond}} \) values and their dependence on age in a normal adult population. On the one hand, early physiological studies using the phase III slope of the single breath washout (SBW) following a 1 litre oxygen inhalation have indicated an age dependence of ventilation heterogeneity.\(^{17,18} \) In later studies, age dependence of the vital capacity SBW phase III slope—which includes a gravitational component\(^{19} \)—was found to be either non-existent,\(^{20} \) or poor up to the age of 55–60 years.\(^{21,23} \) On the other hand, histological evidence,\(^{24} \) and indirect measurement by MRI,\(^{25} \) have demonstrated alveolar size increases in the normal lung between 25 and 65 years. This is expected to impact on ventilation heterogeneity in the most peripheral acinar lung units (potentially affecting \( S_{\text{acin}} \)) but also on the elastic properties of clusters of acini (potentially affecting \( S_{\text{cond}} \)).

We therefore hypothesised that while \( S_{\text{acin}} \) is the most likely MBW index to be age dependent, \( S_{\text{cond}} \) and LCI may be affected by age as well.

### MATERIALS AND METHODS

MBW tests were collected on never-smoker healthy subjects in the age range 25–65 years, in two laboratories (\( n=120 \)). To test the potential for automated analysis of such large MBW datasets for future clinical use, similar to that previously done for the SBW test,\(^{20} \) we also submitted a data subset for semi-automated analysis recently developed by a third participating laboratory.\(^{29} \) The study protocols at UZ Brussel (core dataset site) and Brompton Hospital (supplemental dataset site) were approved by the respective local research ethics committees (B14320097554; 08/H0709/2). All participating subjects were Caucasian, were not obese (described as a body mass index \( >30 \)) and were defined as healthy through clinical screening according to the following: an absence of history of symptoms suggestive of respiratory disease, no childhood or past medical history of respiratory disease, and had never smoked. Subject recruitment was undertaken through open advertisement in an intention-to-enter manner to avoid potential bias or lack of representativeness of the population at large. All subjects provided written informed consent prior to testing.

**Core dataset (UZ Brussel; \( n=120 \))**

After standard spirometry, MBW and SBW tests were performed in triplicate on 120 subjects (15 men/15 women in each decade between 25 and 65 years of age). The MBW test involved 1 litre tidal breathing from functional residual capacity (FRC). The SBW test was performed as two previously used maneuvers\(^{17,18,20} \): either a one-litre inspiration from FRC with expiration to residual volume (SBW\(_{\text{FRC}}\)) or a vital capacity inspiration with expiration back to residual volume (SBW\(_{\text{RV}}\)). A bag-in-box and valve system was used, with a re-inspired dead space (ie, re-inspired volume in subsequent MBW inhalations) amounting to 50 ml, and a \( N_2 \) analyser (PK-Morgan, Rainham, UK).

**Supplemental dataset (Brompton Hospital; \( n=60 \))**

After spirometry, MBW tests were performed in triplicate on 60 subjects between 25 and 65 years, with an even spread of gender across the age range studied. The equipment was very similar to the UZ Brussel bag-in-box setup, with a re-inspired dead space of 15 ml, and a \( N_2 \) analyser (Logan Research, Rochester, UK).

After accounting for synchronisation between \( N_2 \) and pneumotachograph signals and re-inspired dead space specific to core and supplemental datasets, MBW tests were analysed as per the instructions provided by one of the authors (MP) common to the present and the original paper on MBW analysis.\(^{8} \) To this end, custom-built manually operated software was used by authors SV and MP to determine phase III slopes (nominally between 0.65 and 1 litre) from each breath of the MBW test. The phase III slopes were normalised by the mean expired \( N_2 \) concentration, plotted against lung turnover, and \( S_{\text{acin}} \) and \( S_{\text{cond}} \) were calculated after pooling all valid normalised slopes from the three MBW tests;\(^{9} \) a typical example is shown in the online supplement. Additionally, LCI was computed as the number of lung turnovers when mean expired \( N_2 \) concentration had reached 1/40th of the pretest alveolar \( N_2 \) concentration; this was also done on the average of three \( N_2 \) concentration washout curves (each with washout curve normalised to its pretest alveolar \( N_2 \) concentration); the rationale and impact of using mean expired or end-tidal concentration for LCI computation is discussed elsewhere.\(^{22} \) From the SBW tests (pertaining to the core dataset), the phase III slope was determined over the entire expiration down to residual volume, and normalised by mean expired concentration. Depending on the SBW starting volume (FRC or RV), the normalised phase III slope is referred to as \( S_{\text{III}_\text{FRC}} \) or \( S_{\text{III}_\text{RV}} \). For the SBW manoeuvre starting from RV, the phase III slope is also reported as a non-normalised phase III slope (\( S_{\text{III}_\text{RV}} \); in %/litre) for ease of comparison with the literature.\(^{20,23} \)

### Statistical analysis

All statistical analyses were performed using MedCalc (V.10.4, Mariakerke, Belgium). Variables were tested for normality using the \( \chi^2 \) test. Multiple stepwise regressions were performed on \( S_{\text{acin}} \), \( S_{\text{cond}} \), LCI, \( S_{\text{III}_\text{FRC}} \) (log transformed), \( S_{\text{III}_\text{RV}} \) and \( S_{\text{III}_\text{RV}} \) (log transformed), including gender, age, height and FRC as independent variables. A forward regression was used, setting the inclusion criterion for retention at \( p<0.05 \). When gender was retained as a significant factor, the multiple regression analysis was repeated for each gender. Plots of standardised residuals against standardised predicted values were visually inspected for the validity of linearity and homoscedasticity. Analysis of covariance was used to test for differences in \( S_{\text{acin}} \), \( S_{\text{cond}} \) and LCI between the datasets from the two laboratories (factor: laboratory; covariate: age). Statistical significance was accepted at \( p<0.05 \). Bland Altman plots were used to examine agreement between manual MBW analysis by experts and semi-automated MBW analysis.

### RESULTS

Summary data from the core and supplemental datasets are given in table 1; the table also includes SBW data from the core dataset. Figures 1–3 show the \( S_{\text{acin}} \), \( S_{\text{cond}} \) and LCI increase as a function of age. In the multiple regression analyses on \( S_{\text{acin}} \), \( S_{\text{cond}} \) and LCI values of the core dataset, height or FRC did not reach statistical significance for inclusion in the regression model, while age was a significant contributor to all three MBW indices (\( p<0.001 \); \( S_{\text{acin}} \) was the only index showing a significant gender dependence (\( p=0.002 \)). Age-dependent regression equations corresponding to the core dataset can be found in table 2, with gender-specific equations only for \( S_{\text{acin}} \). When dividing the regression slopes by the value obtained for a subject corresponding to the middle of the age range under study (45 years), these relative increases of \( S_{\text{acin}} \), \( S_{\text{cond}} \) and LCI ranged 0.4–1.2% per year of increasing age. For comparison to SBW data in the literature, regression equations are also included for SBW-derived phase III slopes (table 3). In addition to age, height and FRC were independent predictors.
depending on the SBW maneuver and phase III slope normalisation. In fact, in the case of the vital capacity SBW, the phase III normalisation method determined whether the slope was different between both genders or not (SnIII_RV vs SIII_RV).

The panels B of figures 1 compare the core dataset to the supplemental dataset for $S_{\text{acin}}$, $S_{\text{cond}}$ and LCI. Analysis of covariance showed no difference between laboratories for $S_{\text{acin}}$ and $S_{\text{cond}}$, whereas LCI was significantly lower in the supplementary versus the core data set (mean LCI difference $0.54; p<0.0001$). The prediction of why such a difference should be more pronounced for LCI than for $S_{\text{acin}}$ or $S_{\text{cond}}$, and some additional experiments to verify this, can be found in the online supplement. Also included in an online supplement are the specifications of an automated MBW analysis, applying a recently proposed break point algorithm. Using this technique, we re-analysed half the core dataset (in order of subject entry) and the resulting Bland–Altman plots in figure 4 show that, for the most difficult parameters to obtain automatically ($S_{\text{acin}}$ and $S_{\text{cond}}$), a good agreement between automated and manual analysis was obtained.

**DISCUSSION**

While normal ageing has been shown to be associated with decreased lung compliance and decline in airway diameter, little is known about intrapulmonary heterogeneity of these changes with age. Since ventilation heterogeneity involves dynamic processes, and cannot be reduced to static morphometric properties such as airway wall thickness, physiological tests of ventilation heterogeneity are the only way to investigate this. In the present study, we have quantified the age-dependent

### Table 1  Group data

<table>
<thead>
<tr>
<th></th>
<th>Core dataset (n = 120)</th>
<th></th>
<th>Supplemental dataset (n = 60)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Women (n = 60)</td>
<td>Men (n = 60)</td>
<td>Women (n = 30)</td>
</tr>
<tr>
<td></td>
<td>Avg  SD*</td>
<td>Avg  SD</td>
<td>Avg  SD</td>
</tr>
<tr>
<td>Age (years)</td>
<td>45.1  11.3</td>
<td>44.5  11.3</td>
<td>44.8  12.5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166  5</td>
<td>179  7</td>
<td>162  7</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>63  9</td>
<td>80  11</td>
<td>65  16</td>
</tr>
<tr>
<td>FEV₁ (litres)</td>
<td>2.9  0.4</td>
<td>4.1  0.8</td>
<td>2.7  0.6</td>
</tr>
<tr>
<td>FVC (litres)</td>
<td>3.6  0.5</td>
<td>5.2  0.9</td>
<td>3.4  0.6</td>
</tr>
<tr>
<td>$FEV_{1}/FVC$ (%)</td>
<td>79  5</td>
<td>79  4</td>
<td>79  7</td>
</tr>
<tr>
<td>MBW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRC (ml)</td>
<td>2839  491</td>
<td>3800  807</td>
<td>2673  585</td>
</tr>
<tr>
<td>$S_{\text{cond}}$ (litre⁻¹)</td>
<td>0.035  0.014</td>
<td>0.034  0.010</td>
<td>0.036  0.018</td>
</tr>
<tr>
<td>$S_{\text{acin}}$ (litre⁻¹)</td>
<td>0.083  0.030</td>
<td>0.099  0.032</td>
<td>0.086  0.037</td>
</tr>
<tr>
<td>SBW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$SnIII_{\text{FRC}}$ (litre⁻¹)</td>
<td>0.059 (0.052 to 0.069)</td>
<td>0.050 (0.043 to 0.058)</td>
<td>0.053 (0.020 to 0.022)</td>
</tr>
<tr>
<td>$SnIII_{\text{RV}}$ (litre⁻¹)</td>
<td>1.16 (1.04 to 1.47)</td>
<td>1.04 (0.89 to 1.12)</td>
<td></td>
</tr>
</tbody>
</table>

*When a variable was not normally distributed, median (95% CI) is shown instead.

Avg, average; FEV₁, forced expiratory volume in one second; FRC, functional residual capacity; FVC, forced vital capacity; LCI, lung clearance index; MBW, multiple breath washout; RV, residual volume; SBW, single breath washout; $S_{\text{cond}}$, $S_{\text{acin}}$, multiple breath washout index of conductive and acinar ventilation heterogeneity; $SnIII_{\text{FRC}}, SnIII_{\text{RV}}$, normalised phase III slope of a single breath washout maneuver starting from functional residual capacity or residual volume; $SIII_{\text{RV}}$, unnormalised phase III slope of a single breath washout maneuver starting from residual volume.

**Figure 1** Scatterplots of $S_{\text{acin}}$ versus age. (A) Core datasets with corresponding regression lines for women (open symbols; dashed line) and men (closed symbols; solid line). (B) Core dataset pooling women and men (closed squares; dotted line) and supplementary dataset (crosses; solid line) with corresponding regression lines. $S_{\text{acin}}$ ventilation heterogeneity generated peripheral to the acinar entrance.
change of ventilation heterogeneity in different lung zones via
the MBW test, demonstrating a significant age dependence on
S_{acin}, S_{cond} and LCI in healthy never-smoker subjects. Height
was shown not to have a significant impact on any of the three
MBW indices under study, and gender affected only S_{acin}. The
age dependence of S_{acin} was very similar across both gender
subgroups (figure 1A). The largest absolute S_{acin} difference
between men and women (estimated at 65 years (table 2):
0.025/litre) was small with respect to values encountered in
disease when S_{acin} typically amounts to 0.2 litre^{-1} in moderate
asthma^{13} and rises to 0.3–0.4 litre^{-1} in patients with chronic
obstructive pulmonary disease depending on the presence of
emphysema.\textsuperscript{10} Nevertheless, when setting up clinical studies for
early detection purposes, the gender dependence of S_{acin} may
need to be taken into account.

The slightly greater S_{acin} in men could have suggested that the
intra-acinar bifurcation pattern that is a major determinant of
acinar ventilation heterogeneity is more asymmetric in men.

However, we contend that the observed gender difference in
S_{acin} is more likely due to the fact that inherent to MBW, S_{acin} is
based on a normalised phase III slope from an exhalation that
has been truncated at 1 litre instead of exhalation to residual
volume. This can be inferred from comparison of S_{acin} with the
SBW-derived SnIII_FRC, which is computed from an exhalation
that continues to residual volume, such that all acinar ventila-
tion heterogeneities can fully contribute to the phase III, that is,
to its slope and to the mean expired concentration (by which the
phase III slope is to be normalised). When dividing the
maximum S_{acin} difference between men and women (occurring
at 65 years: 0.025/litre) by its average S_{acin} value (0.111 litre^{-1})
predicted from the equations in table 2, we obtain a relative
difference between men and women of 22%. The corresponding
number based on the prediction equations in table 3 for
SnIII_FRC amounts to only 3% (in this case, average heights and
weights from table 1 are used to compute the predicted values
for men and women of SnIII_FRC). At lower ages the

![Figure 2](image2.png)

**Figure 2** Scatterplots of S_{cond} versus age. (A) Core datasets with corresponding regression lines for women (open symbols; dashed line) and men
(closed symbols; solid line). (B) Core dataset pooling women and men (closed squares; dotted line) and supplementary dataset (crosses; solid line)
with corresponding regression lines. S_{cond}, ventilation heterogeneity generated in the conductive lung zone.

![Figure 3](image3.png)

**Figure 3** Scatterplots of LCI versus age. (A) Core datasets with corresponding regression lines for women (open symbols; dashed line) and men
(closed symbols; solid line). (B) Core dataset pooling women and men (closed squares; dotted line) and supplementary dataset (crosses; solid line)
with corresponding regression lines. LCI, lung clearance index.
dependence of $S_{\text{acin}}$ and $S_{\text{III,FRC}}$ on gender is even reversed, depending also on the choice of FRC and height in the case of $S_{\text{II,FRC}}$. Hence, we conclude that the gender dependence of $S_{\text{acin}}$, which is not negligible with respect to the low $S_{\text{acin}}$ values in normal subjects, is an intrinsic feature of MBW normalised phase III slope analysis and a tradeoff to enable the distinction between acinar and conductive ventilation heterogeneities in lung disease.

Distinct gender differences were observed in the very first physiological investigations of the age dependence of ventilation distribution,\textsuperscript{17,18} using the phase III slope derived from the SBW maneuver starting from FRC. While this was in large part due to absence of phase III slope normalisation, later studies using the vital capacity SBW maneuver also showed a gender difference in phase III slope.\textsuperscript{20,23} For this SBW maneuver, the $S_{\text{III,RV}}$ difference is opposite to that for $S_{\text{acin}}$ essentially due to a slightly greater RV/TLC in women versus men.\textsuperscript{20,23} For expired concentration in the present study, the gender gap normalising the vital capacity SBW phase III slope by mean phase III slope.\textsuperscript{20,23} For this SBW maneuver, the $S_{\text{III,RV}}$ vital capacity SBW maneuver also showed a gender difference in absence of phase III slope normalisation, later studies using the maneuver starting from FRC. While this was in large part due to

\begin{align*}
\text{LCI, lung clearance index; } S_{\text{cond}}, S_{\text{acin}}, \text{multiple breath washout index of conductive and acinar ventilation heterogeneity.}
\end{align*}
Previous studies have shown $S_{\text{acin}}$ and $S_{\text{cond}}$ to be reproducible (eg. Dowmie et al. 15), and the inter-subject differences in $S_{\text{acin}}$ and $S_{\text{cond}}$ that are not related to age should be interpreted in terms of inter-subject differences in lung structure. Based on the fundamental principles laid out in the online supplement, it is reasonable to assume that $S_{\text{acin}}$ and $S_{\text{cond}}$ are particularly associated with subject-specific heterogeneity of lung structures in a way that is very different from spirometric volumes. For instance, $S_{\text{acin}}$ is critically dependent on average acinar branching asymmetry as well as on parallel variability in branching asymmetry,33 which is likely to be different between subjects despite similar overall lung architecture. The same is probably true for $S_{\text{cond}}$, which is subject to heterogeneity in pressure-volume characteristics of lung units larger than acini and heterogeneity in bronchomotor tone of conductive airways subtending these.9

Two computational sources of variability of phase III slope analysis, particularly in normal subjects, are relatively flat phase III slopes, and perturbations from cardiogenic oscillations. These phase III features are particularly challenging when trying to automate computation, but we show here that this is certainly feasible (figure 4). The fact that in lung disease phase III slopes are greater and cardiogenic oscillations are mostly absent makes automated slope computation a realistic option with a perspective of practical clinical applicability. In the early days of computing power, automation of SBW phase III slope calculation was pursued with the perspective of using it as an epidemiological tool.28 In the SBW, automation was aimed at determining the break point between phase III and phase IV20 while for the MBW the issue is finding the break point between phase II and phase III.29

In summary, it has long been known that non-invasive measurement of gas concentrations at the mouth of a patient can provide important information about ventilation heterogeneity, and be a marker of structural abnormality in the small airways. A consistent finding in the present MBW study is that ventilation becomes gradually more heterogeneous as adults grow older between the age of 25 and 65 years, both in conductive and acinar lung zones. The extent of age dependence with respect to intrinsic variability of the MBW indices clearly shows that age is a crucial parameter to be factored in when using these MBW indices as diagnostic tools. Finally, from the methodological issues covered in the online supplement we can summarise that the re-inspired instrumental dead space volume plays a predictable role, with the most marked effect on LCI, and that the MBW analysis in terms of $S_{\text{acin}}$ and $S_{\text{cond}}$—requiring phase III slope determination—can be automated.

**Contributors** Study design, data acquisition, analysis, and writing up results: all authors. Interpretation and supervision of final draft: SV, BRT, OSU.

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**Ethics approval** Research ethics committees of UZ Brussel (B14320097554) and Brompton Hospital (08/H0709/2).

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