Inhaled smoke volume, puffing indices and carbon monoxide uptake in asymptomatic cigarette smokers

G. WOODMAN, S. P. NEWMAN, D. PAVIA AND S. W. CLARKE
Department of Thoracic Medicine, Royal Free Hospital and School of Medicine, London

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Summary

1. Nine asymptomatic smokers each smoked one cigarette of their usual brand on four separate occasions.

2. The inhaled smoke volume was measured by tracing the smoke with the inert gas $^{81}$Kr. Puffing indices were recorded by using an electronic smoking analyser and flowhead/cigarette holder. The expired air carbon monoxide concentration was measured immediately before and within 5 min of finishing smoking.

3. The inhaled smoke percentage (total inhaled smoke volume/total puff volume) averaged 46% to 85% in different subjects.

4. Neither the mean inhaled smoke volume per puff nor the total inhaled smoke volume per cigarette was significantly correlated with any of the puffing indices.

5. Smokers took significantly smaller and shorter puffs, left longer between puffs and inhaled less smoke as the cigarette was smoked ($P < 0.01$), although the proportion of the puff which was subsequently inhaled did not change significantly.

6. There was no significant intra-subject difference in any index from one visit to another.

Key words: carbon monoxide, cigarette smoking, inhaled smoke, puffing indices.

Abbreviations: EEUCO, end-expired carbon monoxide concentration; COHb%, carboxyhaemoglobin concentration%; ISV, inhaled smoke volume; PV, puff volume.

Introduction

The amount of smoke a smoker draws into his mouth and his breathing patterns during smoking have been described [1, 2]. It has, however, been recognized that smokers do not necessarily inhale all the smoke puffed; some of the smoke may be lost by being either allowed to drift out of or forcibly expelled from the oral cavity before inhalation [3, 4]. Consequently, puff volume measurements may give a misleading impression of the quantity of smoke actually inhaled. In this study a radiotracer technique has been used to directly measure the volume of smoke taken into the lungs [5–9]. Puff indices have also been measured, so it has been possible to quantify the proportion of the smoke puffed which is subsequently inhaled. The carbon monoxide concentration in expired air has been measured to investigate whether the increase from smoking a single cigarette is related to puff and inhaled smoke volumes. In order to assess the consistency of the smoking manoeuvre from one visit to the next, nine smokers were monitored four times each.

Subjects and methods

Subjects

Nine asymptomatic smokers were investigated, seven male and two female (subjects 2 and 6). The median (range) of age, smoking and cigarette details were: age 26 (20–42) years, cigarettes/day 22 (15–30), years smoking 10 (3–25), cigarette yield (mg): tar 16 (16–18), nicotine 1.3 (1.3–1.5), CO 16 (16–19). All subjects smoked low to middle or middle tar cigarettes.

Spirometric lung function tests were performed on all subjects, volumes were corrected to body temperature and pressure saturated with water.
vapour and the greatest of three measurements was used [10]. Results are expressed as percentages of predicted values [11, 12]. The forced vital capacity was 106 (94–120)% and the forced expiratory volume in 1 s was 105 (94–129)%; these were determined using a dry bellows spirometer (Vitalograph). The peak expiratory flow rate was 91 (73–114)%, measured with a Wright peak flow meter. Maximum expiratory flow rates at 50% ($V_{max,50}$) and 25% ($V_{max,25}$) of vital capacity were 83 (52–127)% and 83 (53–144)% respectively, measured with an Ohio 840 spirometer equipped with a Bryans X–Y plotter: these indices were less than 75% in only one subject.

**Protocol**

In a preliminary visit to the laboratory the subjects were familiarized with the procedure and performed lung function tests. Subjects were instructed to abstain from smoking for at least 1 h before four subsequent visits, which were separated by approximately 1 week. They smoked a single cigarette of their usual brand in a laboratory free from disturbances and were discouraged from talking whilst smoking.

**Flowhead measurements**

Puff indices (puff volume, puff duration and puff interval) were measured with a smoking analyser (Filtrona Instruments & Automation Ltd, model SAP4). This instrument includes an orifice type flowhead/cigarette holder connected to two MKS 223 differential pressure transducers by 2 m length flexible tubes. A microprocessor based system provided flow and pressure measurements as well as recordings of puff volume, duration and inter-puff interval. A miniature thermocouple (RS Components Ltd) was incorporated in the flowhead between the cigarette filter and the orifice to sense the smoke temperature; puff volume measurements were corrected for deviations from the flowhead calibration temperature of 22°C [13].

**Radiotracer technique**

A radiotracer technique based on that described previously by Sheahan et al. [5, 6] was used to monitor the inhaled smoke volume, here defined as the volume of smoke from the burning tip of the cigarette which was subsequently inhaled. Details of this technique have been described elsewhere [7, 8]. Briefly, air at a flow rate of 200 ± 10 ml/min was used to elute $^{81}$Kr ($E_\gamma = 191$ keV, $T_{1/2} = 13$ s) from a generator. The krypton–air mixture was fed into a chamber of volume approximately 100 ml, which weighed less than 70 g. The flowhead/cigarette holder fitted into one end of the chamber; there was a one-way outlet valve at the other end and a rubber sleeve enclosing the cigarette. An inner aluminium mesh prevented the sleeve from touching the cigarette but did not inhibit gas exchange within the chamber; an outer mesh surrounded the sleeve so that the chamber could be held in the hand. A puff drawn from the chamber and cigarette creates a subatmospheric pressure in the chamber; this causes the closure of the outlet valve and the gradual collapse of the sleeve with negligible resistance. Less than 1% of the puff volume is drawn through the cigarette paper. Radiolabelled smoke inhaled with each puff was detected by a single probe scintillation counter, collimated to view the whole lung field, placed in front of the chest.

Before each cigarette was smoked a calibration was carried out to relate the maximal whole lung count rate to the volume of radiotracer inhaled: volumes of 20, 40, 60, 80 and 100 ml were completely inhaled and a calibration factor in millilitres per counts/s was calculated by linear regression. With regard to the accuracy of the calibration and inhaled smoke volume measurements, the repeatability of the calibration was checked by carrying out the procedure three times; the greatest difference between the calibration factors was 1.5%. A subject trained to inhale completely took puffs from the chamber with puff volumes ranging from 15 ml to 90 ml; the radioactivity was detected and the inhaled volume calculated by using the calibration factor. The difference between the puff volume measurement and inhaled smoke volume measurement was greatest (5 ml) at the largest volume and only 0.6 ml at the smallest volume. The effect of changing the rate and depth of inhalation was investigated by inspiring 40 ml volumes five times each, slowly ( < 0.5 litre/s), quickly (> 3 litres/s) and at three different depths. The greatest difference in the results was less than 2% at different inhalation rates and less than 1.5% at different inhalation depths [7].

**Smoking indices**

The total inhaled smoke volume and the total puff volume were calculated for each cigarette and the ratio was defined as the 'inhaled smoke percentage'. The total inhaled smoke volumes and puff volumes were divided by the number of puffs to obtain the mean inhaled and puff volumes. The lighting puff was not included in any of the indices. To investigate any changes in the indices from the beginning to the end of the cigarette, the inhaled smoke volume, puff volume, ratio of inhaled smoke volume to puff volume, puff duration and puff inter-
val were calculated for the first four puffs (stage I) and last four puffs (stage II) of the cigarette [1].

The carbon monoxide concentration in a sample of end-expired air (EECO) was measured immediately before smoking and within 5 min of finishing the cigarette. Different methods of measuring expired air CO concentrations led to systematically different results [14]. In this study the CO concentration was measured with a Series 2000 Ecolyzer (Energetics Science) after breath-holding. The subject inhaled maximally and then breath-held for 20 s; on exhalation the dead space air was cleared before an end-expiratory sample was collected for analysis [15]. The increase in EECO after smoking over the pre-smoking level was termed ‘EECO boost’ and expressed in parts per million. A correlation was looked for between the EECO boost and puff volume and inhaled smoke volume indices.

Ethical considerations

Radiotracer studies were approved by the Ethical Practice Committee of the Hospital and the Administration of Radioactive Substances Advisory Committee (ARSAC). The radiation dose to subjects was less than 0.01 mGy per cigarette. Subjects gave informed consent in writing.

Statistical analyses

Since the sample sizes for statistical analysis were small, it has not been assumed that experimental data were from a normal distribution and non-parametric tests of statistical significance have been used [16, 17]. The tests used were: Wilcoxon’s rank sum test for pair differences, Spearman’s rank correlation test and Friedman’s two-way analysis of variance by ranks [18]. A probability value of, or less than, 0.05 was taken to indicate statistical significance.

Results

The median and range of each index by visit number are shown in Table 1. Friedman’s two-way analysis of variance by ranks did not show significant variation in any index from one visit to another. Since each subject smoked four cigarettes the data from all 40 cigarettes were not treated as statistically independent; since no significant intra-subject variation was found the data for each subject were pooled [2]. Inter-subject differences are shown in Table 2 by the median of each index over the four visits for each subject. There was a 3.4-fold difference in the total inhaled smoke volume and a 2.9-fold difference in the total puff volume. The median inhaled smoke percentage varied within each subject (Fig. 1) and ranged from 46.0% to 85.0% in different subjects.

Significant correlations between indices were looked for in the data in Table 2 by using Spearman’s rank correlation test: each index was tested against every other index. The total inhaled smoke volume correlated with the mean inhaled smoke volume \( r = 0.76, P < 0.05 \), though neither correlated with any other index. The total puff volume correlated with the EECO boost \( r = 0.77, P < 0.05 \), with the number of puffs \( r = 0.71, P < 0.05 \) and with the puff interval \( r = -0.72, P < 0.05 \). The EECO boost did not correlate with the mean puff volume \( r = 0.62, P > 0.05 \). No other significant correlations were found.

Indices for stage I and stage II of the cigarette were compared by using Wilcoxon’s test for pair differences (Table 3). In comparison with stage I,

<table>
<thead>
<tr>
<th>Index (unit)</th>
<th>Visit number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Total inhaled smoke volume (ml)</td>
<td>380 (201–568)</td>
</tr>
<tr>
<td>Total puff volume (ml)</td>
<td>639 (284–1006)</td>
</tr>
<tr>
<td>Number of puffs</td>
<td>13.0 (8–19)</td>
</tr>
<tr>
<td>Mean inhaled smoke volume (ml)</td>
<td>25.1 (17.0–43.7)</td>
</tr>
<tr>
<td>Mean puff volume (ml)</td>
<td>47.9 (32.0–59.0)</td>
</tr>
<tr>
<td>Puff duration (s)</td>
<td>1.6 (1.1–3.1)</td>
</tr>
<tr>
<td>Puff interval (s)</td>
<td>18.0 (6.7–36.6)</td>
</tr>
<tr>
<td>Inhaled smoke percentage (%)</td>
<td>61.2 (44.4–77.4)</td>
</tr>
<tr>
<td>Total smoking time (s)</td>
<td>255 (127–376)</td>
</tr>
<tr>
<td>EECO boost (p.p.m.)</td>
<td>4.0 (1.5–12.0)</td>
</tr>
</tbody>
</table>
**TABLE 2. Inter-subject variation in smoking indices**

Data are the median index of the four visits for each subject. The total inhaled smoke volumes and puff volumes were divided by the number of puffs to obtain the mean inhaled and puff volumes.

<table>
<thead>
<tr>
<th>Index (unit)</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Total inhaled smoke volume (ml)</td>
<td>342</td>
</tr>
<tr>
<td>Total puff volume (ml)</td>
<td>633</td>
</tr>
<tr>
<td>Number of puffs</td>
<td>13.0</td>
</tr>
<tr>
<td>Mean inhaled smoke volume (ml)</td>
<td>26.3</td>
</tr>
<tr>
<td>Mean puff volume (ml)</td>
<td>48.3</td>
</tr>
<tr>
<td>Puff duration (s)</td>
<td>2.4</td>
</tr>
<tr>
<td>Puff interval (s)</td>
<td>23.7</td>
</tr>
<tr>
<td>Inhaled smoke percentage (%)</td>
<td>52.7</td>
</tr>
<tr>
<td>Total smoking time (s)</td>
<td>304</td>
</tr>
<tr>
<td>EECCO boost (p.p.m.)</td>
<td>3.3</td>
</tr>
</tbody>
</table>

**FIG. 1.** Inhaled smoke percentage for each subject at visit 1 (▲), 2 (■), 3 (●) and 4 (▼).

**TABLE 3. Changes in puff and inhalation indices between stage I, first four puffs (excluding the lighting puff), and stage II, last four puffs**

Median of stages I and II for all cigarettes. Significant changes were found with the Wilcoxon test of pair differences, the median and range of which are shown. NS, Not significant.

<table>
<thead>
<tr>
<th>Index (unit)</th>
<th>Stage I (median)</th>
<th>Stage II (median)</th>
<th>Pair differences [median (range)]</th>
<th>Significance (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhaled smoke volume (ISV) (ml)</td>
<td>41.9</td>
<td>21.5</td>
<td>13.4 (−0.1−27.4)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Puff volume (PV) (ml)</td>
<td>53.7</td>
<td>42.0</td>
<td>22.1 (−3.7−36.3)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Puff duration (s)</td>
<td>2.3</td>
<td>1.4</td>
<td>−0.5 (−1.6−0.1)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Puff interval (s)</td>
<td>13.0</td>
<td>17.8</td>
<td>4.1 (−0.6−6.3)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>ISV/PV (%)</td>
<td>63</td>
<td>62</td>
<td>−1 (−19−16)</td>
<td>NS</td>
</tr>
</tbody>
</table>
during stage II subjects took smaller and shorter puffs, left longer between puffs and inhaled less smoke. These changes were significant at the 1% level. However, the proportion of the puff volume which was subsequently inhaled did not change significantly.

Discussion

The inability to quantify the amount of smoke inhaled is a deficiency in previous studies of the smoking manoeuvre, in which only puffing indices have been measured [1-4, 19]. In the present study accurate measurements of the volume of smoke inhaled into the lungs have been made. The mean inhaled smoke volume was consistently less than the mean puff volume, as illustrated in Fig. 2; also the total inhaled smoke volume was consistently less than the total puff volume. Inhaled smoke volume indices did not correlate with the other indices, suggesting it is not possible to infer the mean or total inhaled smoke volumes from other indices.

There was no correlation between the EECO boost and the mean inhaled smoke volume or total inhaled smoke volume; this result merits further discussion. There are two aspects to carbon monoxide levels in relation to cigarette smoke exposure. One relates to the measurement of chronic exposure where a raised absolute CO level indicates that a subject smokes, the other is the boost in the CO level from smoking a single cigarette. Both the EECO and the absolute carboxyhaemoglobin concentration (COHb%) are chronically raised in smokers. It has been shown that there is a good correlation between EECO and COHb% in epidemiological studies [20-22]. However, in studies where a single cigarette has been smoked, it has been found that the COHb% boost and EECO boost follow different time courses during and immediately after smoking [23]. This may be because EECO but not COHb% measurements are affected by changes in ventilation and/or perfusion during smoking [24].

In unpublished work, we have found that the EECO boost declines rapidly in the first 5 min after smoking. Thus, although the COHb% boost may be a reliable indicator of smoke inhalation from a single cigarette, the same is not true of the EECO boost when measured within the first 5 min after smoking. This may be the reason in the present study for the lack of correlation between the EECO boost and the volume of smoke inhaled from a single cigarette. We suggest that the correlation between the EECO boost and the total puff volume may be a spurious result in view of the time course of EECO boost after smoking. Other studies where the CO boost has been calculated have either found a poor correlation with spirometric measures of inhalation [2] or failed to find a correlation with smoking patterns [1] or with the dose of smoke presented to the smoker [25].

Though the number of puffs taken by smokers varied, analysis of the first and last four puffs has shown that the puff volume and puff duration decrease while the puff interval increases as the cigarette is smoked: these results are consistent with those of other workers [1]. In this study we have also found that the inhaled smoke volume decreases in proportion to the puff volume. This may be due to initial loss of satisfaction from the cigarette or due to the increase in smoke concentration as the cigarette is smoked. At the beginning of the cigarette some of the smoke condenses on the remaining tobacco. When this tobacco is burnt it liberates the condensed smoke constituents as well as its own; the smoke therefore has a higher concentration of tar and nicotine, which leads to it being smoked less intensely.

It has been reported that changes in the environmental conditions and mental state of a smoker lead to changes in the smoking manoeuvre [26-28]. In order to keep the conditions the same and the subject relaxed some workers have provided reading material or background music [2, 19, 29]; others have not reported doing so [30-32]. In this study the subjects sat comfortably in a quiet laboratory and smoked undistracted; they were discouraged from talking to the investigator, who sat out of sight but within hearing distance. It must be recognized that in order to perform an experiment and collect data, it is not possible to have an entirely 'normal' environment; though in this study, the subjects felt their smoking manoeuvre was not affected greatly by the conditions. As in previous studies [1, 2, 33,
34], the group was consistent in its smoking manoeuvre from one cigarette to the next. There is therefore no evidence of subjects adjusting their smoking manoeuvre as they became more accustomed to the apparatus and procedure.

In conclusion, smokers do not inhale all the smoke they take into their mouths and the proportion of the puff which is inhaled varies within and between smokers. The volume of smoke inhaled by a smoker cannot be inferred from puff indices made at the mouth or the increase in expired air carbon monoxide concentration: it has to be measured directly.

Acknowledgment

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References

Cigarette smoke inhalation


