Variations in Amounts of Tobacco Tar Retrieved from Selected Models of Smoking Behavior Simulated by Smoking Machine*

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SUMMARY
The observation was made of variations in human cigarette smoking habits. This suggested that examination by an analytic smoking machine be undertaken to discover whether yields of tobacco tar in simulations of these habits might differ. It was found in various experiments that: (a) Smoking a given number of puffs over a long period of time results in greater tar retrieval than smoking them over a short period. (b) Taking most of the puffs at the end of the cigarette results in the highest tar retrieval, puffing at regular intervals throughout the life of the cigarette gives the next largest yield, and taking most puffs at the beginning, the smallest retrieval. (c) Puffs taken at the end of a cigarette yield about twice the tar of puffs taken at the beginning.

Further research is being conducted on lung cancer and control patients to determine possible differences in the extent to which they exhibit high and low tar-retrieval models.

A large number of investigations dealing with both animals and humans, retrospectively and prospectively, utilizing a variety of research designs, and in several different countries have discovered close relationships between cigarette smoke and tars and the development of cancer at exposed sites. Data on patients at Roswell Park Memorial Institute are typical in showing a risk of lung cancer approximately 6 times higher among cigarette smokers than among nonsmokers (3). At the same time, it is observed that not all smokers develop this disease. Smokers who do and do not develop lung cancer are of interest because knowledge of differences in their response to cigarette smoke, or in the methods of smoking they utilize, may further elucidate characteristics predisposing to or protecting against lung cancer. Comparisons of nonsmokers who do or do not develop lung cancer of specific histologic types could be instructive in similar fashion.

The present research developed out of an interest in the possible variations in methods utilized in smoking cigarettes by lung cancer cases and controls. If certain methods were found to characterize cancer cases more than controls, information might be at hand out of which preventive measures could be fashioned. If it were found, furthermore, that those models of smoking behavior which are peculiar to lung cancer patients also expose the smoker to more tar, additional evidence would be available implicating tobacco tar as a carcinogen. Observations of individuals smoking cigarettes in public places such as bus, railroad, airline, and hospital waiting rooms, and in hotel lobbies in the Buffalo area, revealed that humans exhibit a number of variations in smoking behavior. Details of these variations will be described in a later paper, but it can be noted here that there were large differences in the number of puffs taken on a given cigarette by smokers, in the length of time taken to smoke a cigarette to the point at which it is extinguished, and in the length of time taken to smoke a given number of puffs. Furthermore, it was observed that the frequency of puffing often varied at different stages in the smoking of a given cigarette. Three patterns of puffing behavior were observed: puffing at approximately equal frequency throughout the life of a cigarette; taking puffs slowly at the beginning of

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the cigarette and increasing their frequency toward the end; and puffing most frequently immediately after lighting the cigarette and gradually diminishing the frequency toward the end of the cigarette.

After the discovery of these variations, further studies were conducted to examine the extent to which these variations characterized patients at Roswell Park Memorial Institute, as will be discussed in a later paper. It was found that a given smoker fairly consistently exhibited a given kind of smoking behavior from one cigarette to another.

The conclusion that the patterns observed were probably real led us to begin two types of studies: first, a comparison of the smoking patterns of lung cancer and control patients to discover whether differences in smoking patterns might exist, and second, a simulation of the various patterns on an analytic smoking machine to determine whether the yield of tar from smoking according to each pattern varies. The first study continues. The present paper reports on the second. Briefly, it was found that smoking a given number of puffs over a long period of time yields more tar than smoking them over a short period, that increasing puffing frequency toward the end of a cigarette results in more tar than smoking more frequently at the beginning, and that puffs taken toward the end of a cigarette contain more tar than those taken at the beginning.

**MATERIALS AND METHODS**

Sequences of experiments, to be described in the findings, were utilized to examine the tar yields of various models of smoking behavior. Throughout these experiments one brand of cigarette was utilized. Before a given experiment, a carton was selected from a stored lot, and enough packages chosen from the carton to provide cigarettes meeting the conditions of the research. One of these was that, when the air resistance of the cigarette was measured, the negative pressure required to draw 17.5 ml/sec of air through the cigarette was between 2 and 2½ inches of water. Those outside the range were discarded as were cigarettes outside the weight range of .948-1.01 gm. Those of like weights within that range were allocated to each of the experimental groups.

Subsequent to measuring air resistance and weighing, in all sequences except II, IV, and V, cigarettes were individually wrapped in aluminum foil and put aside in order of weight until use on the same day. Cigarettes were always inserted into the smoking machine receptacles with the brand name out. They were carefully ignited with an electric lighter so as to obtain a uniform light over the complete end of the cigarette. The cigarettes were protected from drafts while burning, and were extinguished after the last puff in a series. Butt length was recorded. A number of cigarettes was smoked in each experiment to provide sufficient tar for accurate measurement and lessened variation. Each experiment was completed in a single day to control factors such as daily variations in humidity and the possible effect of such a variation on tar retrieval.

The Ecusta Smoking Machine utilized in these experiments is of the analytic type and has the capacity to produce smoke under a variety of controlled conditions (5). Twenty cigarettes can be puffed serially for 2 seconds each. To achieve variations in frequency, the cigarettes were moved to different positions manually in sequences I–V. A small amount of smoke was lost in this process. Although this loss was equally distributed among experimental groups, in later sequences the hoses leading from the piston to the smoking positions were moved from position to position, as the design demanded, with minimal loss of smoke. The machine was adjusted to give a puff volume of 35 ml. in 2 seconds.

In sequences I–III, and the first two experiments of sequences IV and V, the tar was obtained through condensing it at −70° C. in a helical glass coil surrounded by dry ice in alcohol. This was washed out with 25 ml of 3:2 alcohol:toluene and the solvent evaporated in a 50°–60° C. oven for 5 hours to obtain dry tar weight. Optical density of the tar solution was also measured, at 375 mλ. In subsequent experiments, the collecting coil was replaced by two filling funnels. Without alteration of its temperature the smoke was drawn through a Cambridge filter clamped between the tops of the funnels. The filters were weighed before and after the tar was trapped on them. Only filters of similar weight prior to use were employed in the experiments. It was found that all three methods of measuring tar gave comparable results.

The experiments of sequences I, III, VII, and VIII were pilot experiments in that it was in these that the above-mentioned methods were developed. The findings in them are deemed to be either incomplete or unreliable. This paper, therefore, reports only on experiments in sequences II, IV–VI, IX, and X.

**RESULTS**

*Sequences IV and V*—The hypothesis to be tested in these sequences of experiments was that smoking a given number of puffs over a long period of time provides a greater yield of tar than

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1 Filter Media 101, Cambridge Filter Corp., Syracuse, N.Y.
the same number of puffs taken over a short period of time.

Cigarettes in sequence IV were smoked for 12 minutes, over which time seven puffs were taken at regular intervals of 2 minutes between puffs. Those in sequence V were also puffed 7 times but at equal 1-minute intervals and over a period of 6 minutes. Both the periods of time and the numbers of puffs are well within the ranges exhibited by the human smokers we observed. In each experiment except D and E three sets of two cigarettes each were smoked according to the design of sequences IV and V. Experiments D and E utilized only two sets of cigarettes. Experiment C was dropped because of machine malfunction. In all, we report on ten experiments, each of which was completed on a single day.

In spite of the fact that the same number of puffs were taken in each sequence, the mean butt lengths yielded from sequence IV, utilizing the long period of time, were 22.1 ± 1.2 mm. shorter than those of sequence V, using the short time period ("" = 31.5, P < .01).

Table 1 shows the mean tar retrieved per two cigarettes in the 28 sets comprising the two experiments. Two sets of the 28 showed no difference between sequences IV and V. These were in the first two experiments in which measurements of tar retrieved were derived from condensation in coils and drying. In each of the other sets, cigarettes smoked slowly—i.e., seven puffs over 12

<table>
<thead>
<tr>
<th>Model</th>
<th>Butt length/cigarette (mean±S.D.)</th>
<th>Tar retrieved in five cigarettes (mean±S.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>21.4±1.86</td>
<td>.145± .055</td>
</tr>
<tr>
<td>B</td>
<td>21.1±1.75</td>
<td>.161± .020</td>
</tr>
<tr>
<td>C</td>
<td>19.6±2.06</td>
<td>.173± .021</td>
</tr>
</tbody>
</table>

2. Taking twelve puffs at regular time intervals over 8 minutes.

3. Taking most puffs toward the end of the cigarette—i.e., the second puff 2 minutes after lighting, the next three puffs at regular intervals over 4 minutes, and the last seven puffs in regular intervals over 2 minutes.

In each experiment, a total of twelve puffs were taken on five cigarettes smoked according to each of the above models in a given 4-hour period. Average relative humidity based on readings at the beginning, middle, and end of each day's run revealed no relationship to tar retrieval. Table 2 shows the average length/butt after smoking the five cigarettes in each of seven experiments, and the average gm. tar retrieved from the total of five cigarettes in each experiment.

In each of the seven experiments, smoking according to Model C—i.e., with most puffs taken at the end of the cigarette—resulted in a considerably larger amount of tar retrieved than when most puffs were taken at the beginning of the cigarette. In all but one experiment, where the lengths were the same, smoking according to Model C resulted in a shorter butt length than did Model A. In addition, it is of interest that Model B, with twelve puffs taken at regular intervals, resulted in a tar retrieval which in all experiments except the first was intermediate between those of Models A and C. Table 3 reveals that the

**TABLE 1**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Tar retrieved (mean±S.D.) (gm.)</th>
<th>Butt length (mean±S.D.) (mm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV, Seven puffs in 12 minutes</td>
<td>.041±.0046</td>
<td>12.6±1.6</td>
</tr>
<tr>
<td>V, Seven puffs in 6 minutes</td>
<td>.083±.0042</td>
<td>34.6±1.6</td>
</tr>
<tr>
<td>Difference between IV and V</td>
<td>.008±.0047</td>
<td>22.0±1.9</td>
</tr>
</tbody>
</table>

minutes, yielded more tar than those smoked seven puffs over a 6-minute period of time. The mean difference in the amount of tar recovered from cigarettes in sequence IV versus sequence V, .008 ± .0047 gm., is significant. This is 24.2 per cent of the tar retrieved using sequence V.

**Sequence IX**—These experiments were tests of the hypothesis that three different models of cigarette smoking would result in different retrievals of tar. The models were:

1. Taking most puffs at the beginning of the cigarette—specifically, of a total of twelve puffs, taking the first seven in the first 2 minutes after lighting, the next four puffs in regular intervals over 4 minutes, waiting 2 minutes, and taking the last puff.

2. Taking twelve puffs at regular time intervals over 8 minutes.

3. Taking most puffs toward the end of the cigarette—i.e., the second puff 2 minutes after the lighting puff, the next three puffs at regular intervals over 4 minutes, and the last seven puffs in regular intervals over 2 minutes.

In each experiment, a total of twelve puffs were taken on five cigarettes smoked according to each of the above models in a given 4-hour period. Average relative humidity based on readings at the beginning, middle, and end of each day's run revealed no relationship to tar retrieval. Table 2 shows the average length/butt after smoking the five cigarettes in each of seven experiments, and the average gm. tar retrieved from the total of five cigarettes in each experiment.

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mean differences in amounts of tar retrieved in comparing each of the smoking models with the other are statistically significant. Thus, over all experiments, puffing frequently at the end of the cigarette yields a mean of .030 ± .0088 gm. more tar than puffing frequently at the beginning, and .018 ± .0051 gm. more than puffing at regular intervals. Puffing regularly results in .018 ± .0104 gm. more than puffing most frequently at the beginning. Briefly stated, puffing frequently at the end of a cigarette gives a mean result of 21.0 per cent more tar than puffing frequently at the beginning and 7.4 per cent more than puffing regularly. Puffing regularly yields 12.6 per cent more than puffing frequently at the beginning.

Sequences II, VI, and X.—The observation that smoking the same number of puffs slowly produces more tar than smoking them over a short period of time, and that taking puffs more frequently at the end produces more tar than taking them at the beginning of the cigarette, suggested that cigarette length at the moment a given puff is taken may affect the tar retrieved from it. Thus, in smoking slowly, a larger proportion of the total puffs are taken on a short butt than is true when puffing more frequently. The same is true when smoking the majority of puffs at the end of the cigarette as in Model C, sequence IX. The fact that the puffs are taken on a shorter butt means that less tobacco is present to filter tar from the smoke. A second factor making for a greater tar retrieval is the possibility that the smoke which is accumulated in the unburned part of the cigarette is burned and adds to the tar content of smoke when that part of the cigarette is finally consumed (1).

It was hypothesized, therefore, that later puffs taken on a given cigarette contain more tar than ones taken shortly after lighting. Put another way, it was hypothesized that the shorter the butt, the more tar retrieved from puffs on the cigarette. Sequences II and VI examine the first version of the hypothesis and sequence X the second version.

Sequence II consisted of five experiments measuring the amount of tar taken in each puff separately of fifteen cigarettes smoked at the rate of one puff every 51 seconds. Experiment A was discarded because of errors in tar measurement technic.

Table 4 shows that in each experiment, B, C, D, and E, the tar for a given puff, considered separately, increased as the number of puffs increased, although not in a directly linear fashion. Thus, although there was general increase, there was a decline noted in the fifth to the eighth puff and another decrease in the last two or three puffs on the cigarettes. It will be noted that Experiment C follows this trend, but at a lower level than the other experiments. No satisfactory explanation for the difference in this experiment is available, but it is interesting to note that whatever variable was introduced was done so systematically, since its effect was apparently evenly distributed over all puffs taken. The trends of increasing tar retrieval with increases in the number of puffs are reflected in all experiments in measuring tar both by dry weight and optical density.

The experience of sequence II suggested that it was possible that some smoke was escaping measurement through the manual moving of cigarettes to different receptacles on the smoking machine. For this reason, sequence VI was designed, which did not demand the removal of cigarettes until smoking was finished. Analyses with this procedure yielded results essentially similar to those of sequence II.

In an effort to shift our point of measurement from the consideration of puffs per time unit, sequence X was devised to enable us to measure the results of smoking various lengths of the cigarette. It was necessary to divide the cigarette into as many units of length as possible so as to allow the fullest possible examination of tar retrieval. Because of variations in length of cigarette consumed in the 2-second puff utilized, usually about 3 mm., at least a 4-mm. unit had to be used. Usually it took about 45 seconds for the cigarette to burn the remainder of the unit length after the 2-second puff was taken. New puffs were taken whenever a given 4-mm. unit was reached, regardless of time elapsed. Sixteen cigarettes were smoked on a given day; a set of eight cigarettes was smoked to one of the 4-mm. sections designated, and the other set of eight was smoked to the adjacent 4-mm. section. All the tar from a complete set of eight cigarettes was collected on

TABLE 3

DIFFERENCES IN GRAMS OF TAR RETRIEVED FROM SMOKING FIVE CIGARETTES ACCORDING TO THREE MODELS, MEANS FOR SEVEN EXPERIMENTS

<table>
<thead>
<tr>
<th>Models</th>
<th>Mean difference</th>
<th>&quot;t&quot;</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (frequent puffing at end) — A (frequent at beginning)</td>
<td>.030 ± .0088</td>
<td>9.09</td>
<td>&lt; .01</td>
</tr>
<tr>
<td>B (regular puffing intervals) — A (frequent at beginning)</td>
<td>.018 ± .0104</td>
<td>4.50</td>
<td>&lt; .01</td>
</tr>
<tr>
<td>C (frequent at end) — B (regular intervals)</td>
<td>.012 ± .0051</td>
<td>6.32</td>
<td>&lt; .01</td>
</tr>
</tbody>
</table>
a given filter, and the difference in tar retrieval between the two sets measured.

Chart 1 thus indicates the mean differences observed in weights of tar retrieved from smoking adjacent length categories starting with 12 mm. This procedure of smoking two sets to adjacent 4-mm. categories and thereby obtaining the difference in tar retrieval between the two was repeated 4 or 5 times to obtain each mean shown in Chart 1.

TABLE 4
TAR RETRIEVED FROM EACH OF TWELVE PUFFS TAKEN AT 15-SECOND INTERVALS ON FIFTEEN CIGARETTES IN EACH OF FOUR EXPERIMENTS

<table>
<thead>
<tr>
<th>Puff No.</th>
<th>Experiment</th>
<th>MEAN DRY WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>Dry weight (gm.)</td>
<td>Optical density</td>
</tr>
<tr>
<td>1</td>
<td>.025</td>
<td>.45</td>
</tr>
<tr>
<td>2</td>
<td>.028</td>
<td>.48</td>
</tr>
<tr>
<td>3</td>
<td>.021</td>
<td>.62</td>
</tr>
<tr>
<td>4</td>
<td>.032</td>
<td>.72</td>
</tr>
<tr>
<td>5</td>
<td>.039</td>
<td>.77</td>
</tr>
<tr>
<td>6</td>
<td>.038</td>
<td>.76</td>
</tr>
<tr>
<td>7</td>
<td>.036</td>
<td>.85</td>
</tr>
<tr>
<td>8</td>
<td>.037</td>
<td>.85</td>
</tr>
<tr>
<td>9</td>
<td>.040</td>
<td>1.10</td>
</tr>
<tr>
<td>10</td>
<td>.042</td>
<td>.95</td>
</tr>
<tr>
<td>11</td>
<td>.040</td>
<td>.91</td>
</tr>
<tr>
<td>12</td>
<td>.040</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Mean first three puffs, .026 ± .0045.
Mean last three puffs, .040 ± .0062.
"t" = 6.4, P < .01.

The standard deviations of all but one of these ranged from .0033 to .0064, except for the 40- to 44-mm. segment, which was .016. It appears that, as the cigarette burns shorter, the tar retrieved per puff increases. The mean difference in gm. of tar retrieved in smoking eight cigarettes 12 mm. as compared with 16 mm. is .020, whereas that obtained in smoking between 44 mm. and 48 mm. is .043. It will be noted that, as in sequences II and VI, there is a smaller difference in tar retrieved on the last puff than on that preceding. In this sequence as in VI, the high point of tar retrieval was toward the end of the cigarette and was about twice that of the low point, at the beginning. A similar difference, but slightly smaller, was found for sequence II.

DISCUSSION

The experiments described in this paper suggest that there are variations in the amount of tar retrieved from smoking cigarettes according to different models. Thus, sequences IV and V suggest that more tar is retrieved when the same number of puffs were smoked over a long than a short period of time. Sequence IX gives evidence that, of three models of smoking behavior, that in which most frequent puffing is reserved for the last part of a cigarette yields more tar than when puffs were taken at equal intervals throughout the
life of the cigarette; and that this last model of smoking results in more tar than puffing most frequently immediately after lighting the cigarettes.

These findings suggest that there may be some characteristic of puffs taken in the last segments of cigarettes which result in their yielding more tar than puffs taken at the beginning. Sequences II, VI, and X, developed to test the hypothesis that later puffs or those taken on shorter butts result in higher tar retrieval, each provided a positive finding. This is reminiscent of findings by Lindsey (4), Kotin and Falk (2), and Wynder and colleagues (6–8) in research on related questions.

It is important, of course, to note that whether or not these findings reflect tar exposure to humans smoking according to the different patterns depends on how well the simulation of human models was accomplished by the machine. At the same time, if we find in our current research that lung cancer cases as compared to controls in our patient populations utilize smoking models of higher tar yield, we have further evidence of the carcinogenicity of the tars to human lung tissue. It will be recalled that the Models A, B, and C of sequence IX showed a regular gradation in the amount of tar retrieved. If there is a similar gradation in the per cent of lung cancer cases as compared to controls, with the different models, some further evidence will be available of a dose-response relationship between exposure to tobacco tar and human lung cancer. This would be consistent with those findings which show an increase in lung cancer risk with an increase in amount of cigarettes smoked daily.

It should be noted, too, that, although the differences in amounts of tar retrieved from various models are of small magnitude, they are relatively of substantial size. Puffing frequently at the end of the cigarette resulted in 7.4 per cent greater tar retrieval than puffing regularly, and 21.0 per cent more than puffing most at the beginning. Slow smoking resulted in 24.3 per cent greater retrieval than fast smoking. The exposure of lung tissue over a period of many years to such excesses in amounts of tobacco tar from each cigarette smoked will result in a significantly larger aggregate exposure.

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