Immediate and Sustained Effects of Smoking on Autonomic Arousal in Human Subjects

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Abstract: The effects of smoking on sudomotor/autonomic activity were examined by measuring water transfer across the skin (sweat output) as an index of activity. Sweat output was measured in 14 subjects (11 male and 3 female) during the act of smoking and for about 60 min following this. Sweat output was measured in 5 (4 male, 1 female) controls over the same time period. Smoking had two effects on sweat output: In 12 subjects it caused an immediate increase in output; in 4 of these 12 the increase persisted for the duration of the recording period. In the other 2 subjects no increase was noted, but in no

subject did smoking cause a decrease in sweat output. Mood state questionnaires were administered at the beginning and end of the experimental period. No clear association was found between scores on the mood questionnaires and the autonomic effects of smoking. In 2 subjects, transdermal blood flow was also measured during and after smoking. Smoking caused a decrease in blood flow in these subjects. These results are discussed in terms of the “arousal modulation” hypothesis of smoking. [Japanese Journal of Physiology, 48, 253–259, 1998]

Key words: smoking, arousal, sudomotor activity, neural sweating, nicotine.

Although smoking is among the most addictive habits known, the precise nature of its appeal to humans remains unclear. At the doses normally consumed, nicotine has no clear effects that would seem sufficient to account for the widespread popularity of the habit. One possible explanation of the appeal of smoking was advanced by Mangan and Golding [1], who first formulated the “arousal modulation theory.” This hypothesis proposes that smokers use smoking to produce different subjective effects dependent on their initial state of arousal: When a smoker is agitated, smoking is used to produce a calming effect; when drowsy, smoking is used to increase alertness. Golding and Mangan [2] provided some support for their theory by using EEG patterns as a measure of arousal in laboratory subjects. This work has been criticized because of the extreme laboratory situations used, situations that are of doubtful relevance to normal smoking [3]. Other authors have suggested that smoking may affect stress and arousal separately [4,5]

We have investigated this problem by using a differ-

ent measure of arousal—sudomotor drive, which provides an indirect measure of skin sympathetic drive [6]—as an indicator of the effects of smoking on humans. This involves measuring total transpiration (or water transfer) across the skin surface of a single digit. This water transfer consists of insensible sweating, which sets the “background” level of water transfer, and neural sweating, which reflects activity in the sympathetic nervous system. That activity in this part of the autonomic nervous system is related to arousal and has already been demonstrated [6]. The problems of relating any external measure to an internal state, however, remain. In our study, we have investigated the consequences of the act of smoking under environmental conditions that maintain steady arousal levels and conditions that approximate “everyday” smoking as closely as is reasonable in an experimental setting. In this way we hoped to avoid some of the complications associated with extremes of arousal that have beset some previous investigations (see, for example, Golding and Mangan [2]).

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METHODS

Experiments were conducted on 18 healthy university students from 20 to 27 years old. All subjects participated as paid volunteers. They were divided into two groups. Fourteen (11 male, 3 female) participated as smokers; all smoked at least one cigarette per day. Five (4 male, 1 female) participated as controls, and two of the males in this group were smokers. Subjects were told not to consume tobacco, tea, coffee, alcohol, or carbonated drinks for at least 1 h before the recording session.

Subjects were studied from 10:00 a.m. to 12:00 noon, or from 2:00 p.m. to 4:00 p.m. The experimental room was air conditioned and maintained at a temperature of $23 \pm 0.5^\circ\text{C}$. Relative humidity varied from 30 to 60%. Subjects were separated from the experimenter by a screen and observed via closed circuit television.

Procedures. On arrival at the laboratory, each subject was met by a male experimenter who provided general information about the nature of the experimental apparatus and procedures. Each subject was seated upright at a desk in a comfortable ergonomic chair. The sudorometer (see below), an ashtray, a cigarette lighter, and one subject's cigarettes were placed on the desk. Two subjects had none of their regular cigarettes at the time of the experiment; they smoked a 1.2 mg nicotine cigarette supplied by the experimenter. Both indicated they frequently smoked cigarettes that were not their regular brands. A television set was in front of the desk. After giving informed consent, the subject was asked questions relating to general health and smoking habits. Subjects were then required to complete the modified Mood State questionnaire prepared by O'Neill and Parrott [5]. Before the experimental recording began, subjects selected a "nonstressful" documentary video. Once the subject was comfortable and the output of the sudorometer stable, the experimenter moved behind the screen and was unseen for the rest of the experiment. The video was started after the subject had been seated quietly for 5 min. A period of 10–15 min (adaptation period) was required for water transfer from each subject's finger to reach a steady level. Following this adaptation period, a 15-min recording was made of the "basal" (presmoking) period. At the end of this time, subjects were informed they could smoke whenever they wished. Most elected to do so immediately. Recording continued throughout this period (about 7 min) and for 45–50 min after smoking had ended. At the end of the recording session, the subjects were again required to complete the Mood State question-

naire. After this they were debriefed and paid for their participation. One subject (a smoker) failed to complete both questionnaires correctly. Control and smoking subjects followed identical procedures, except that controls were not instructed to smoke and did not do so.

Measurement of sweat output. Total transpiration across the skin surface was measured as water transfer across finger skin by using a specially designed chamber (see Satchell *et al.* [6] for full details of the chamber and the method). Sweat output is a component of the water transfer and was defined as any rapid change in water transfer. The present study was concerned with the effect of smoking on the frequency and duration of neural sweating. For this reason no attempt was made to measure the total water transfer caused by the act of smoking. This measure would have contained no information about the frequency or duration of the effect and would be confounded by the basal level of water transfer.

The method, briefly, was as follows: The subject's index finger was inserted into the chamber, through which dry nitrogen flowed continuously at $200 \text{ ml} \cdot \text{min}^{-1}$. After passing over the finger, the gas was channeled past a humidity sensor capacitor (Humidity Sensor CCH; CHK Engineering, Sydney, Australia, under license from Commissariat à l'Énergie Atomique, France). The active polymer dielectric of the single capacitor absorbed water linearly in proportion to the relative humidity (RH), producing a proportional change in capacitance. The nominal capacitance at 75% RH was 500 pf, the sensitivity was 1.7 pf/% RH, and the measurement range was 0–100% RH. Any humidification of the chamber with the finger in place was due to moisture produced by the finger. The output of this device was digitized (2 Hz) and stored for off-line display and analysis.

RESULTS

To study the effects of smoking on sweat output, it is necessary to know the effect of the experimental setup (apart from smoking) on this variable. Figure 1 shows traces from five control subjects, monitored for 60 min. Although water transfer was generally constant in these individuals during the experimental period, occasional short-lasting deflections (sweat expulsions) are apparent, superimposed on the baseline water transfer. These correspond to neural sweating and occurred with variable frequency in different individuals. It is clear from these records that the experimental procedure itself caused no systematic changes in either the baseline or the neural sweat output in any

Fig. 1. Sweat traces from the five control subjects. Recordings were started 15–20 min after subjects were attached to the recording system. **A** shows traces from 2 smokers. **B** shows traces from 3 nonsmokers.

Fig. 2. Sweat trace from a smoking subject. The recording was started 15–20 min after the subject was attached to the recording system. The arrow below the trace indicates the time at which the instruction to smoke was given. The two arrows above the trace indicate the period during which the subject actually smoked. Because of the problems of accurate calibration of sudorimeters [14], no attempt was made to convert the arbitrary units of the computer display to relative humidity in the chamber. All recordings were made under essentially identical conditions, and no comparisons of absolute values between subjects were made.

of these subjects. One subject (third trace from the top) touched her nose during the recording period. This produced the only marked deflections in this subject's trace.

No attempt was made to compare the baseline data from this group with that of the experimental group. This was not statistically feasible, and the groups were not selected in a way that would make any valid comparison possible.

Figure 2 (a) shows an example of the sudomotor trace from a smoker before, during, and after the act of smoking. At the first arrow, the subject was in-

Fig. 3. Sweat traces from smoking subjects. Recordings were started 15–20 min after subjects were attached to the recording system. The asterisk below the bottom trace in C indicates the time at which the instruction to smoke was given. **A:** Where there was both initial and sustained responses. **B:** Initial responses only. **C:** Two subjects where there was neither an initial or a sustained response. Numbers at the side of each trace are the average number of cigarettes smoked per day (nicotine content of usual brand). DRUM, beside the fourth trace in A refers to a subject who made his own cigarettes from Drum® tobacco: the nicotine content of this tobacco was not available.

structed to smoke. Note that this caused an increase in water transfer before smoking actually commenced (second arrow). Actual smoking lasted 8 min and was accompanied by a marked increase in sweat output in this subject, which persisted for 2–3 min after smoking ceased (third arrow). This increase, commencing with the instruction and persisting until just after smoking ceased, will be referred to as the immediate response. Following smoking, a sustained increase in the frequency of the sweat expulsions took place in this subject, which persisted for the duration of the recording. This increase will be referred to subsequently as the sustained response.

Figure 3 shows the traces recorded from all experi-

Table 1. Stress and arousal scores for control and experimental subjects before and after recording.

A. Control subjects

Stress		Arousal	
Before	After	Before	After
40	40	80	50
40	60	50	50
30	20	60	50
50	30	70	70
50	30	70	40

B. Experimental subjects

Stress		Arousal	
Before	After	Before	After
40	70	80	60
50	30	40	30
20	20	90	70
60	20	80	30
50	30	60	40
50	40	80	50
70	50	40	20
70	20	100	50
20	20	60	60
30	50	60	40
50	60	70	40
50	70	80	40
50	50	70	40

Both groups completed the modified Mood State Questionnaire [5] before and after the recording period.

mental subjects during and after the act of smoking. The traces have been aligned so that all subjects commenced smoking at the time indicated by the asterisk. The act of smoking lasted from 5–8 min in all subjects. The traces have been grouped into three (subjectively determined) groups. The top 4 traces are from subjects with a clear immediate and a clear sustained increase in sweat expulsions. The middle 8 traces are from subjects with a clear initial response, but with some question whether there was any sustained increase. The bottom two traces are from subjects with no definite initial or sustained responses.

Beside each trace, the frequency of smoking (self-reported) in cigarettes per day and the nicotine content of the cigarettes usually smoked (and employed in the study) are shown. There was no clear systematic relationship between either of these variables and the response recorded, although a tendency appeared for the initial response to be smaller in heavy ($>10/d$) smokers. When the areas under the curves of the initial responses were measured and correlated with cigarette

consumption, however, no significant relationship was detected.

Table 1 lists the anxiety and mood scores of the control and experimental subjects at the beginning and the end of the experimental period. When the subjective scores at the beginning and end of the experimental period were compared in control subjects, no differences were seen, suggesting that the experimental procedure itself did not alter either of these measures. When the subjective scores of smokers at the beginning and end of the experimental period were compared, self-reported arousal was reduced in all but two cases, and the results were significantly different (t -test, $p < 0.003$).

The range of responses seen in different subjects raises the possibility that the response of an individual might be quite different on different occasions. This possibility was tested in a preliminary experiment that was also designed to investigate the effect of changes in ambient temperature on the response to smoking. Figure 4 shows the responses of the same individual on three separate occasions at 19, 23, and 30°C. Although the background ("thermal") sweating increases with increasing temperature, it is clear that in this person smoking produced a qualitatively similar effect (clear immediate response, questionable sustained response) at each of the three temperatures. Certainly some of the differences in baseline activity in different individuals are probably due to individual differences in thermal drive. These differences do not, however, modify the individual's basic response to smoking.

The possibility that the increase in sweat output might be secondary to an increase in blood flow to the skin was investigated in two experiments. Traces from these experiments are shown in Fig. 5. Smoking definitely caused changes in blood flow, but these were in the direction of reduced flow, which would not be associated with an increase in sweat output. In one experiment where blood pressure was measured, it increased at the start of smoking, and this increase was sustained over the measurement period. Similar sustained effects on blood pressure have been reported by Gropelli *et al.* [7].

DISCUSSION

Before we discuss the effects of smoking on sweat output, some comment about baseline levels needs to be made. The sweat output of each individual in the study consisted of transient rises and falls superimposed on a baseline level. In some individuals, a drift in this baseline was observed during the course of the experiment. This raised two questions: first, that such

Fig. 4. Smoking sweat traces from one individual at three different temperatures. **A:** 19°C, **B:** 23°C, **C:** 30°C.

baseline movements might be attributable to the effects of smoking, and second, that the effects of smoking on neural sweating might be modulated by the baseline level. At this stage we can only say that although we do not believe the answer to either of these questions is affirmative, the data are insufficient to be certain of this. The baseline value is the result of output from the sweat glands (neural sweating) and of direct transpiration of water across the skin ("insensible sweating"). Separating these two components was not possible in this study, so we elected not to try to interpret baseline values. The situation is further compli-

Fig. 5. **A:** Simultaneous recordings of water transfer, blood flow, and blood pressure during smoking. **B:** Simultaneous recordings of water transfer and blood flow during smoking.

cated because the neural sweat output of the finger is made up of both emotional and thermal sweating. Because these neural components of sweating were not separated in the present study, the two measures could be blurred. At an ambient temperature of 23°C, at which subjects were tested, it could be predicted that thermal influences would be slight. However, it cannot be determined in the present study whether thermal sweating after smoking remained at the basal levels set by the room temperature.

There was no association between absolute baseline level and any of the parameters measured (smoker vs. nonsmoker; stress level; arousal level), and we believe it is not an important variable. This will be established, however, only by further study.

In the present study, the only significant result relating to arousal was that smokers generally reported reduced arousal at the end of the experimental period. Previous subjective evaluations of arousal (e.g., Parrot [8]) done "immediately" after smoking reported increased arousal. The second test in the present study was administered at least 40 min after the act of smoking. This could explain the difference in results.

Smoking produced two possibly separate effects on sweat output: a transient, short-lasting increase in sweating and a sustained increase in spontaneous ex-

pulsions. These latter have been shown to correspond to spontaneous activity in autonomic nerves by using microneurography [9].

The occurrence of a sustained response was not as clear as that of the initial response. This may be due in part to the variable baseline activity in different individuals before smoking. If a "ceiling" exists for an individual's neural sweating at this temperature, sustained increases might then be difficult to observe above the thermal "noise."

What is clear from all the traces is that smoking did not produce any immediate or sustained reduction of neural sweating. One might have expected a period of "silence" during and/or after smoking in some individuals if the "arousal modulation" theory were correct.

Amplitude of the initial response. Several factors contributed to the amplitude of the initial response. Most subjects had an "anticipatory" component: The expectation of smoking caused an increase in sweat output. A possible additional factor was the physical movement associated with the smoking itself. The contribution of this is presumably variable, but it must have been small because in one subject no initial response was apparent. Although this was clearly an unusual result, it indicates that the response to the act of smoking is more than simply an artifact resulting from arm movements.

Origin of the delayed response. A previous investigation that examined the effects of mental activity (Stroop test, mental arithmetic) on sweat output found that both these activities resulted in an immediate increase in sweating [6]. This increase persisted for some minutes after the task, but in neither case was there any evidence for a long-lasting response comparable to the one observed in the present study in response to smoking. In the third control trace, the subject's movement produced a small immediate increase in sweat output lasting for about 5 min, but no evidence was found of any sustained effect. We thus conclude that a striking effect of the act of smoking is a sustained change in autonomic tone. Any attempt to characterize the mechanism underlying this would now be speculative, but because the half-life of nicotine is 120 min in smokers [10, 11], it could be due to a persistent effect of the drug rather than to a change in some internal state.

Are the effects the result of central or peripheral actions of nicotine? Receptors for nicotine are present in the peripheral and the central nervous system, and it could be argued that some of the effects seen in the present study are the result of ganglionic stimulation. Several lines of evidence sug-

gest that this is not so. First, the levels of nicotine that would have been achieved in the blood of smokers in this study (of the order of 40 ng/ml, based on data from Grassi *et al.* [12]) are several orders of magnitude below those reported to produce effects in autonomic ganglia [13]. Second, if ganglia were stimulated, one consequence should be peripheral vasoconstriction with an accompanying reduction in sweat output. Further evidence that the nicotine ingested during smoking does not stimulate sympathetic ganglia indiscriminately comes from the study of Grassi *et al.* [12]. These authors found no increase in activity in the postganglionic nerves supplying skeletal muscle following smoking. Grassi *et al.* [12], in fact, observed a sustained decrease in firing in the postganglionic nerves supplying skeletal muscle. On the basis of this observation, they suggested that central sympathetic activity is inhibited by smoking. Although this may be true of cardiovascular sympathetic activity, the results of the present study indicate that it is not true for the sympathetic system as a whole—that portion controlling neural sweating undergoing sustained stimulation instead of inhibition. The sustained increase in neural sweating and the sustained decrease in nerve activity in skeletal muscle produced by smoking argues for a central action of nicotine/smoking on central autonomic activity. The opposite effects on different parts of the sympathetic system suggest that the effects of nicotine (assuming the effects in the present study can be attributed to nicotine) on sympathetic drive are complex and are the result of system changes and not of any simple effect on receptors.

Because smoking can produce sustained but opposite effects on different parts of the autonomic nervous system lends weight to the suggestion of O'Neill and Parrott [5] that smoking can affect different aspects of emotional behavior independently. These authors noted that the self-reported behavior of smokers was consistent with their use of smoking to affect arousal and stress independently. If the same dose of nicotine can produce opposite central effects, this interpretation of smokers' behavior is more plausible and probably closer to a description of the real situation than the somewhat simplistic "arousal modulation theory."

CONCLUSION

Our final conclusion is that the act of smoking causes both an immediate and a sustained increase in sweat output. We found no evidence that smoking can both increase and decrease arousal (as measured by sweat output). It does not follow that such a subjective experience does not occur in smokers, but it does suggest

that the hypothesis that smokers use smoking as an arousal modulator needs to be treated cautiously.

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