A SWEAT SENSOR FOR QUALITATIVE MEASUREMENTS

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To study objectively the sweat response during motion sickness, a need existed for a small sweat-sensing device with a short latency of response, a fast response time, and the ability to follow the time course of the sweat response. The design and function of a sweat-sensing device for continuous monitoring of the sweat response are described. A lithium chloride-aluminum chloride sensing element, which changes resistance depending on the uptake or release of moisture, is used in this sensor. The sensing element is enclosed in a housing that is designed to circulate air from the skin surface to the sensing element. Air is supplied from a compressed-air cylinder and is controlled with a needle valve flowmeter assembly. With an air-flow rate of 15 cc/min and in response to a step change in moisture content on the skin surface, the sensor has a latency of 1.5 seconds and a rise time to reach 90 percent of the saturation level of about 28 seconds. A major disadvantage of the sensor is that with heavy sweat rates, the sensing element saturates, resulting in relatively long "drying out" times. This can be partially offset by using higher air-flow rates, but at the expense of reduced sensitivity. The application of this sensor has shown that it is capable of responding to the cyclic sweat activity commonly seen when skin-resistance measurement techniques are used to monitor the sweat response.

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SUMMARY PAGE

THE PROBLEM

To study objectively the sweat response during motion sickness, a need existed for a small sweat-sensing device that could be attached to a subject's skin and at the same time not interfere with the experimental task. Such a sensor must have a short latency of response, a fast response time, and the ability to follow the time course of the sweat response, including recovery to presweat levels.

FINDINGS

The design and function of a sweat-sensing device for continuous monitoring of the sweat response are described. A lithium chloride-aluminum chloride sensing element, which changes resistance, depending on the uptake or release of moisture, is used in this sensor. The sensing element is enclosed in a housing that is designed to circulate air from the skin surface to the sensing element.

With an air-flow rate of 15 cc/min and in response to a step change in moisture content on the skin surface, the sensor has a latency of 1.5 seconds and a rise time to reach 90 percent of the saturation level of about 28 seconds. A major disadvantage of the sensor is that with heavy sweat rates, the sensing element saturates, resulting in relatively long "drying out" times. This can be partially offset by using higher air-flow rates, but at the expense of reduced sensitivity.

The application of this sensor has shown that it is capable of responding to the cyclic sweat activity commonly seen when skin-resistance measurement techniques are used to monitor the sweat response.

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INTRODUCTION

In order to measure objectively the sweat response observed during motion sickness, a need existed for a sensor that could indicate the early onset of sweating. The desirable specifications for such a sensor would include the following:

1. Short latency and fast response time.

2. Capability of following the time course of the sweat response, including recovery to presweat levels.

3. Ability to function during angular rotation.

4. Small size and light weight such that localized sweat responses could be detected without interference with the subject.

In a review of methods for the measurement of sweating, Robinson and Robinson (15) discussed general methods for the study of sweat-gland activity in localized areas. These include: a) collection of water vapor from evaporated sweat, b) direct collection of liquid sweat, c) direct observation of sweat droplets using a microscope, and d) use of color indicators on the skin. Of the above methods the first can be adapted most easily to the rotating environment used during motion sickness studies. As a method for collection of water vapor, several authors (2-4, 10-13) have used a flow-through technique by which dry air picks up moisture as it is passed over the skin surface.

Of the various methods for the detection of the water-vapor content in air, one of the simplest is the use of a transducer that absorbs or releases water, depending on the moisture content of the air, and as a result changes its dc resistance. Dunmore (8, 9) first described a lithium chloride sensor that worked on this principle. Custance (4, 5) used a similar sensing element in his sweat-measurement technique. In his sensor the flow of dry air was altered in such a way that the moisture content of the air and thus the dc resistance of the sensing element always remained constant. The air flow, therefore, served as an indirect measure of the quantity of sweat being produced. The main objection to this sensor would appear to be the increased lag time that results from the requirement for feedback and adjustment of the air flow.

Recently Ackermann (1) developed a sweat detector in which a combination lithium chloride-aluminum chloride sensing element was used. From the point of view of sweat detection, this sensor appeared to have certain advantages over other lithium chloride sensors. However, the sensor housing did not have incorporated in it a flow-through principle such that continuous recordings of sweat output could be monitored. The present report describes the design, function, and application of a flow-through housing for use with the sensing element as developed by Ackermann.

SENSOR DESIGN

SENSING ELEMENT

The sensing element is a lithium chloride-aluminum chloride ($LiCl.H_20-AlCl_3$) transducer developed by Ackermann. The design and construction details of this sensing element are described in his report (1). The sensor works on the principle of varying dc resistance with changes in water-vapor content of the surrounding atmosphere. The advantages of this particular unit are its fast response time, high sensitivity, and resistance to "wash out" (inability to reverse the moisture uptake phase).

$LiCl.H_20$ is one of the most hydroscopic substances known and was first used by Dunmore (8,9) as a humidity transducer. The rise time in response to a change in moisture content of the air can be increased by adding another salt (eg., $AlCl_3$) that does not form a double salt with $LiCl.H_20$. The addition of a second salt acts to reduce the vapor pressure of the saturated aqueous solution formed when moisture is absorbed by the sensitive coating. This increases the difference between the partial pressure of water vapor in the atmosphere and the vapor pressure of the solution of the sensitive layer. This allows for more rapid uptake of water from the surrounding air.

The $LiCl.H_20-AlCl_3$ mixture is bound to a 1.5-cm diameter disk, made from copper-clad PVC board, on which a pair of electrodes are etched.

SENSOR HOUSING

In the original sensor designed by Ackermann the sensing element is enclosed in an air-tight plastic cup. This has two major disadvantages as a sensor to detect the sweat response during motion sickness.

1. Since the water vapor at the skin surface must reach the sensor by diffusion through the air, the latency of the response is increased.

2. Once the sensor saturates, there is no way of removing the water already within the housing should the sweat response decline.

To overcome these problems a housing was designed in which a flow-through principle similar to that of Custance (4) and Edelberg (10) was used.

Figure 1 illustrates a cross-section through the sensor housing.

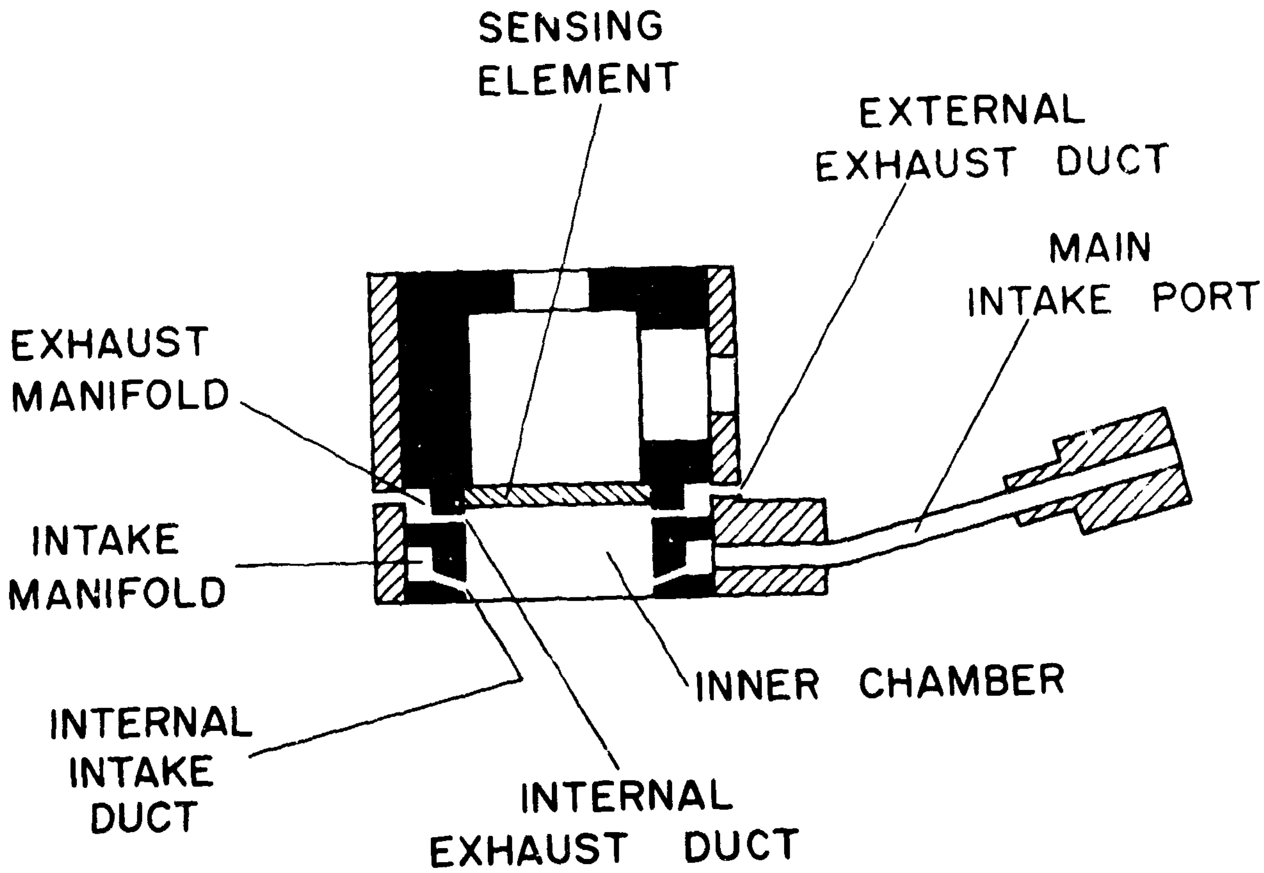

Figure 1

Diagrammatic cross-section of sweat-sensor housing. In actual cross-section internal intake and exhause ducts are not located in the same plane.

Dry air enters the intake manifold through the main intake port. From the intake manifold, air reaches the inner chamber through four internal intake ducts. Each duct lies at a 20-degree angle below the horizontal to direct the inlet air down against the skin. The ducts are also directed in such a way that air enters tangentially to the wall of the inner chamber. This serves to create a swirling motion of the air within the housing. Four internal exhaust ducts leading from the inner chamber are located immediately below the sensing element. With these ducts in this position, the air circulates from the skin surface to the sensing element before being exhausted. Air leaving through the four internal exhaust ducts enters an exhaust manifold before being exhausted to the outside through four external exhaust ducts.

Figure 2 is a photograph of the various parts of an actual sensor prior to assembly, and Figure 3 is a photograph of the sensor in the assembled state. Detailed drawings are provided in the Appendix.

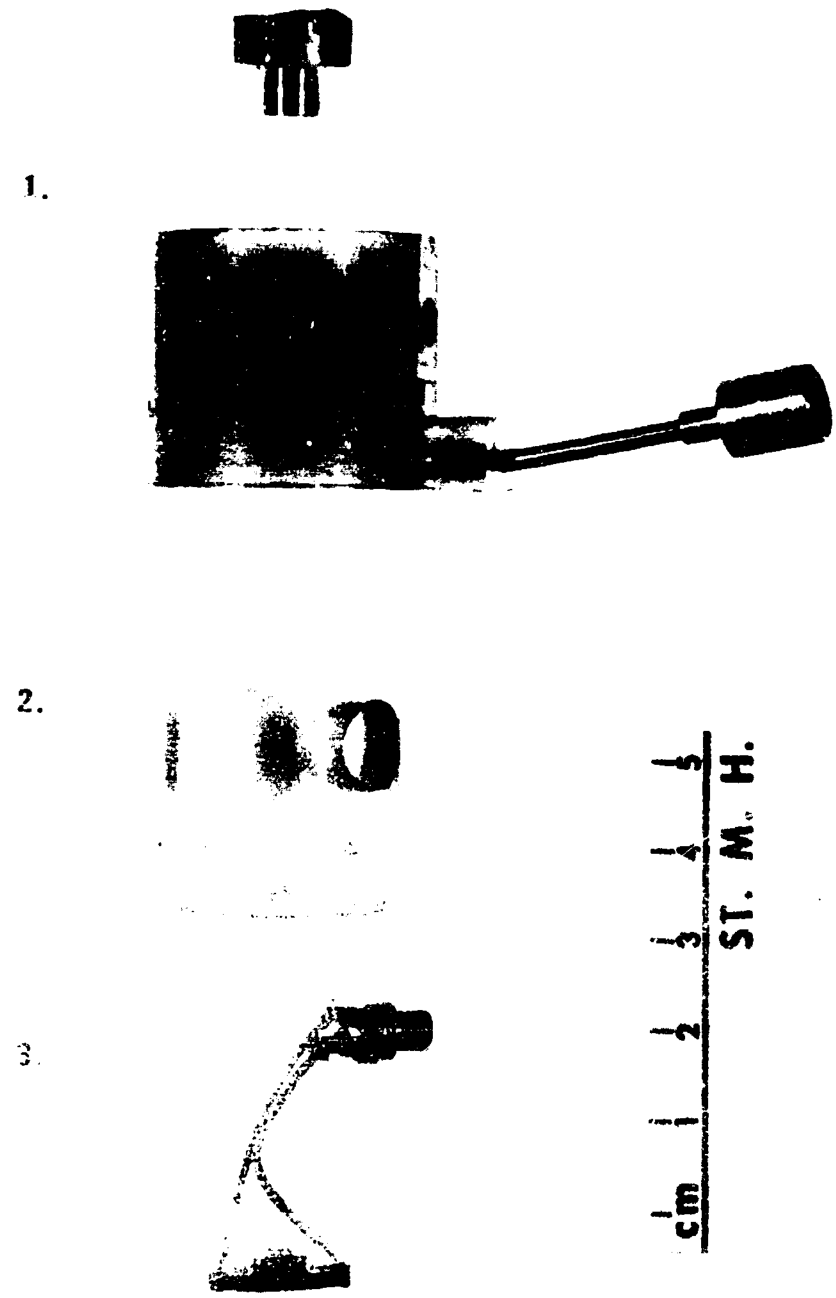

Figure 2

Sweat-sensor parts. From top down: 1) sensing element holding nut; 2) outer housing with needle mount; 3) housing core; 4) sensing element with electrical connector.

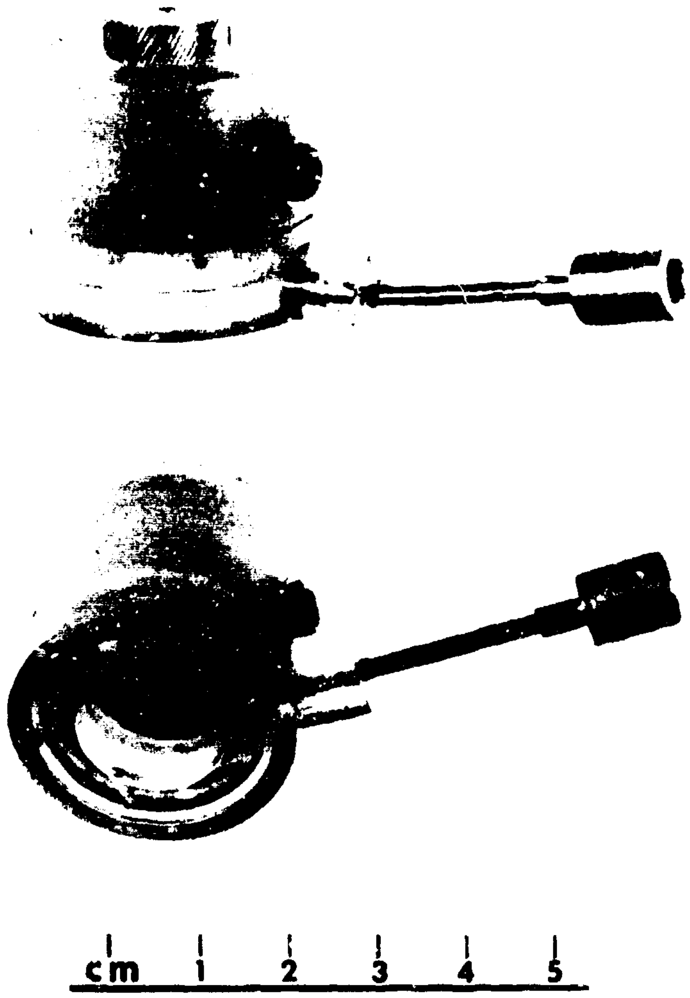

Figure 3

Photograph showing two views of the sweat sensor in the assembled state. In the lower photograph part of the sensing element is visible in the inner chamber.

AIR-SUPPLY SYSTEM

Figure 4 is a diagrammatic illustration of the air-supply system. Air is supplied from a small compressed-air cylinder through a pressure-reducing valve. Air at 3 psig is supplied to a flowmeter (Brooks model 1355 Slow rate "150" with ELF NRS needle control valve) which allows for accurate control and measurement of the air flow to the sensor. Prior to entering the sweat sensor, the air is dried by passing it through a 1.5-foot length of 0.75-inch tubing containing calcium chloride ($CaCl_2$).

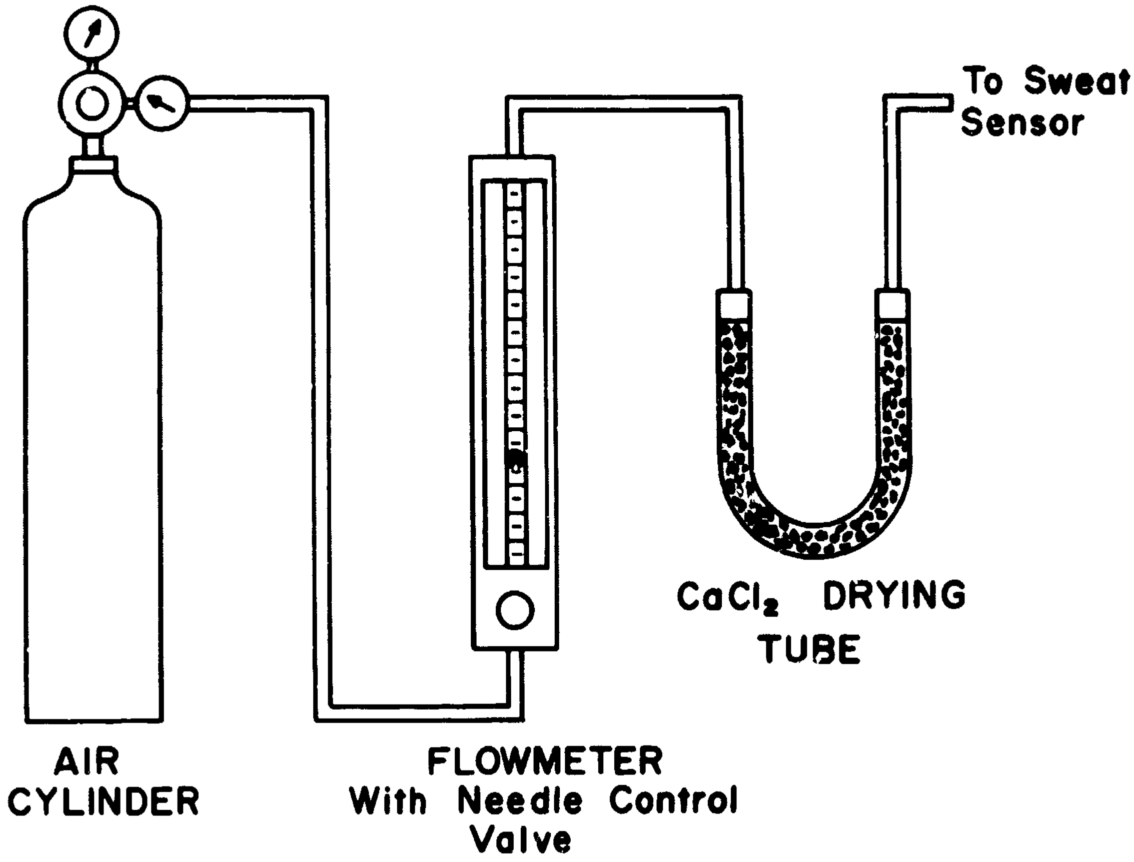

Figure 4

Diagrammatic illustration of air-supply system.

The compressed air used in the system is standard scuba-diving air. The complete system is relatively small in size and easily mounted on a rotating chair for use in motion sickness studies.

SENSOR FUNCTION

SENSOR RESPONSE

Figure 5 illustrates a typical response when the sensor is suddenly exposed to a wet skin surface at skin temperatures of 35°C and 31°C. These curves were obtained by moving the sensor quickly from a dry surface to an area of skin on the dorsal hand moistened with saliva. In the curves of Figure 5, the step change occurred at time zero. The air flow through the sensor was 15 cc/min.* At the higher skin temperature

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* This air flow has been used in all applications of the sensor to date.

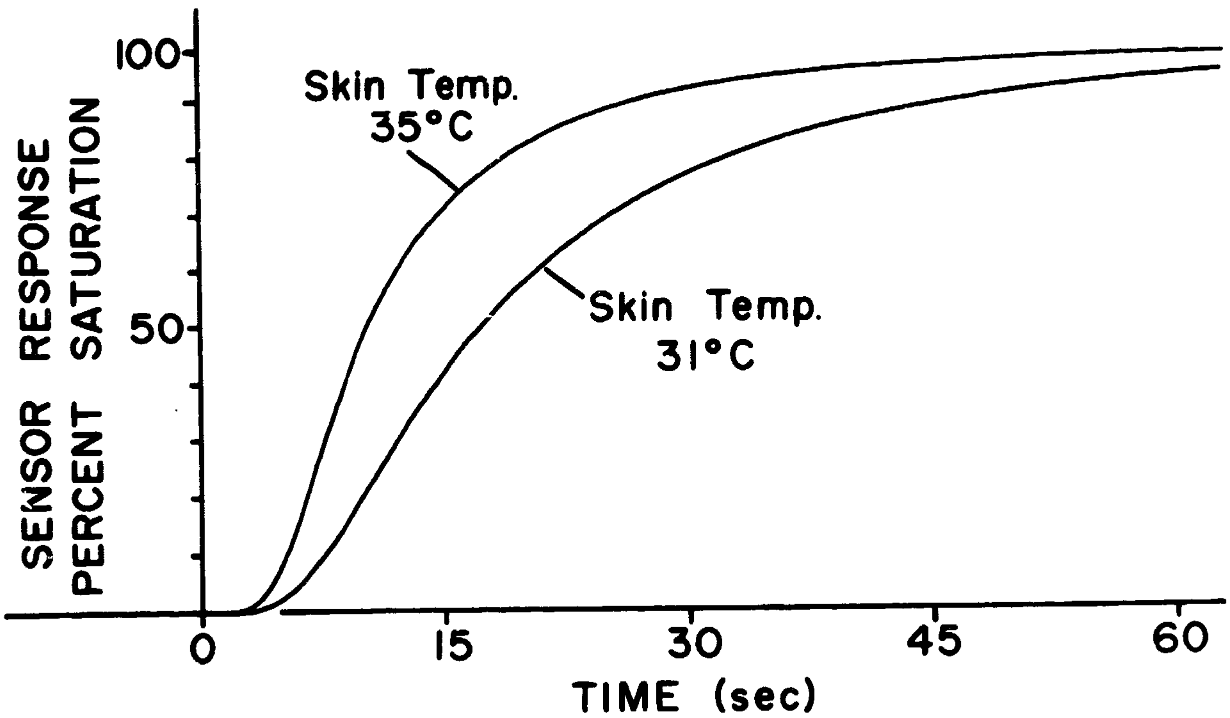

Figure 5

Sensor response on sudden exposure to a wet skin surface at skin temperatures of 35°C and 31°C. Sensor air flow 15 cc/min.

of 35°C, which in this subject represented the normal resting value, the time to reach 90 percent of the saturation level was 28 seconds, although 50 percent of this change occurred within the first 11 seconds.

Of significance is the fact that the response is affected by the temperature of the moisture on the skin. This is not surprising since a fluid at a relatively high temperature will vaporize more readily. In the practical situation the temperature of the sweat can vary significantly, depending on the skin temperature. Pinson (13) demonstrated a similar effect when he showed an increase in insensible perspiration with increased skin temperature. Other authors (2,4) who have attempted to obtain quantitative responses from flow-through sweat sensors have not taken this effect into account.

One of the disadvantages of the sensor is its lack of sensitivity near the saturation region. In addition, once the sensor is saturated, which frequently occurs when the sweat response during motion sickness is monitored, it can take several minutes for the sensor to dry out after the sweat response has stopped. This effect can be reduced by using higher air-flow rates, but with some sacrifice in sensor sensitivity at the lower sweat levels.

SENSOR LATENCY

The curve in Figure 6 illustrates the response with the gain of the output amplifier increased twenty-five times over that used to obtain the curves in Figure 5. Once again the step change occur. . at time zero, and the air flow through the sensor was 15 cc/min. This particular curve peaks and returns to the resting state because the sensor was replaced on a dry surface shortly after the onset of the response and well before it was saturated.

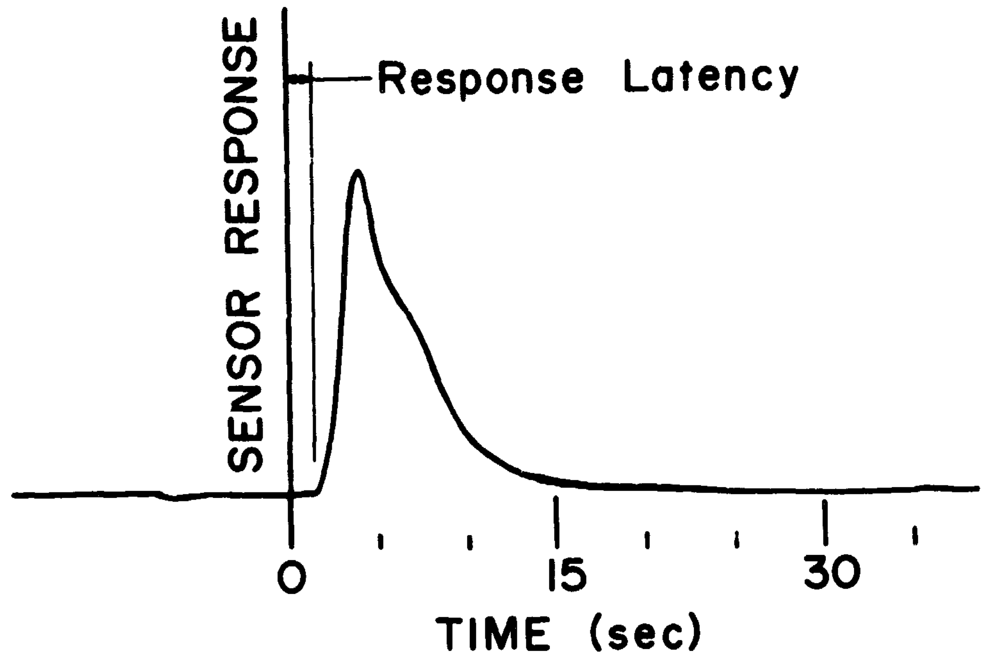

Figure 6

Curve showing latency of sensor response. Output amplifier gain 25 times that of curves in Figure 5. Sensor air flow 15 cc/min.

It can be seen that the latency of the response is approximately 1.5 seconds. This represents the time required for evaporation of moisture from the skin surface, for the moist air to travel from the skin surface to the sensing element, and for absorption of the moisture by the sensing element.

EFFECT OF AIR-FLOW RATE

Figure 7 illustrates the sensor response at low air-flow rates of 10, 20, 30, and 40 cc/min. The step change occurred at time zero, and the zero times for each flow are shifted on the X-axis to separate the curves. In each case the sensor was returned to a dry surface before the saturation level was reached. All curves were obtained with a skin temperature that reflected the resting state of a subject in a 21°C environment.

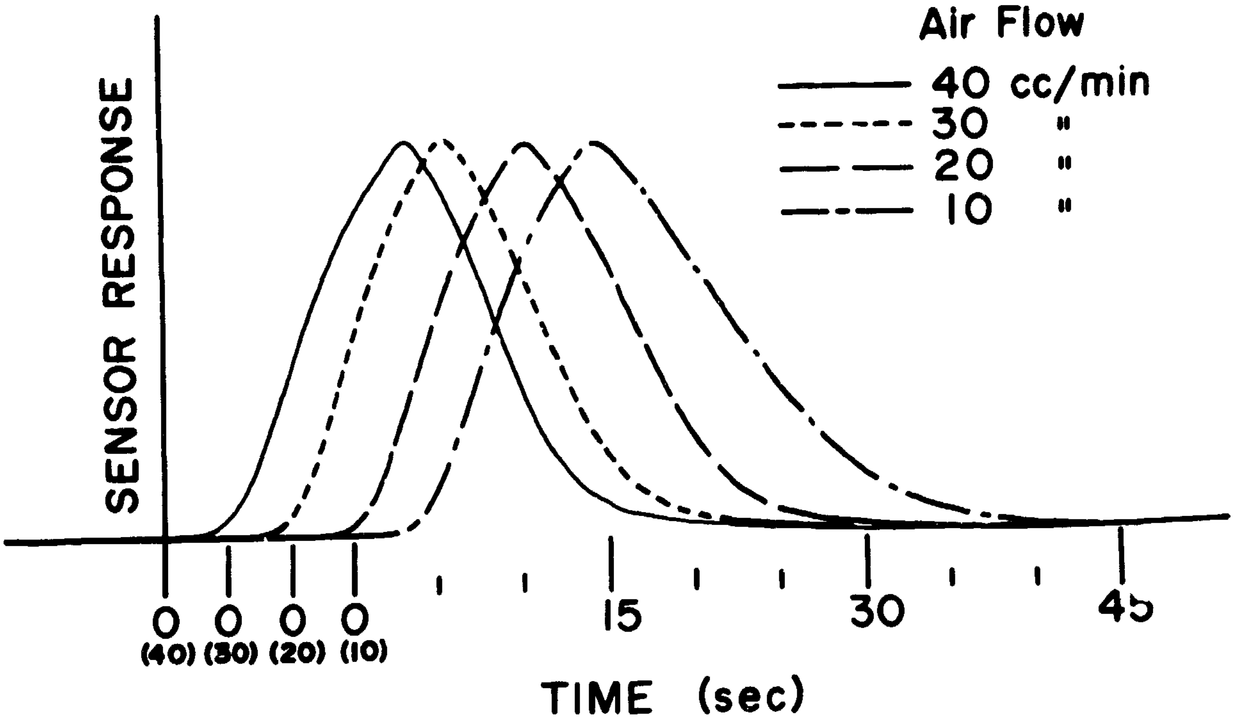

Figure 7

Effect of low air-flow rates on sensor response. Zero times for each flow are shifted on the X-axis to separate the curves.

Comparison of the curves in Figure 7 reveals that at these low air-flow rates, there is very little effect on the rise or fall times of the sensor response. The 40-cc/min curve does show a slightly shorter fall time as compared to the 10-cc/min curve. This becomes more pronounced at very high flow rates, with the additional advantage that the drying-out time following saturation is also shortened. However, as mentioned previously, with such high flow rates the sensitivity at the lower sweat levels is reduced.

SENSOR APPLICATION

The electrochemical sweat sensor (ECS) as described in this report has been in use for approximately 2 years, during which time 200 to 300 experimental runs have been carried out. In all cases the output from the ECS has been compared to the sweat response as detected by skin resistance techniques (SRS).*

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* Commonly called galvanic skin response (GSR) when referring to the sweat response from the palm of the hand.

Figure 8 illustrates an actual trace of the sweat response obtained from the dorsal hand of a subject during the elicitation of motion sickness. The upper and lower graphs are outputs from the ECS; the gain for the lower graph was increased 12.5 times over that for the upper one. The second graph from the top represents the output as measured by the SRS. Changes in skin resistance were detected by means of Beckman miniature skin electrodes and a Sanborn 350-12 GSR bridge as a constant current source. The current was passed in and out across the skin at the two electrode sites. The voltage difference between the two electrodes reflects the changes in skin resistance.

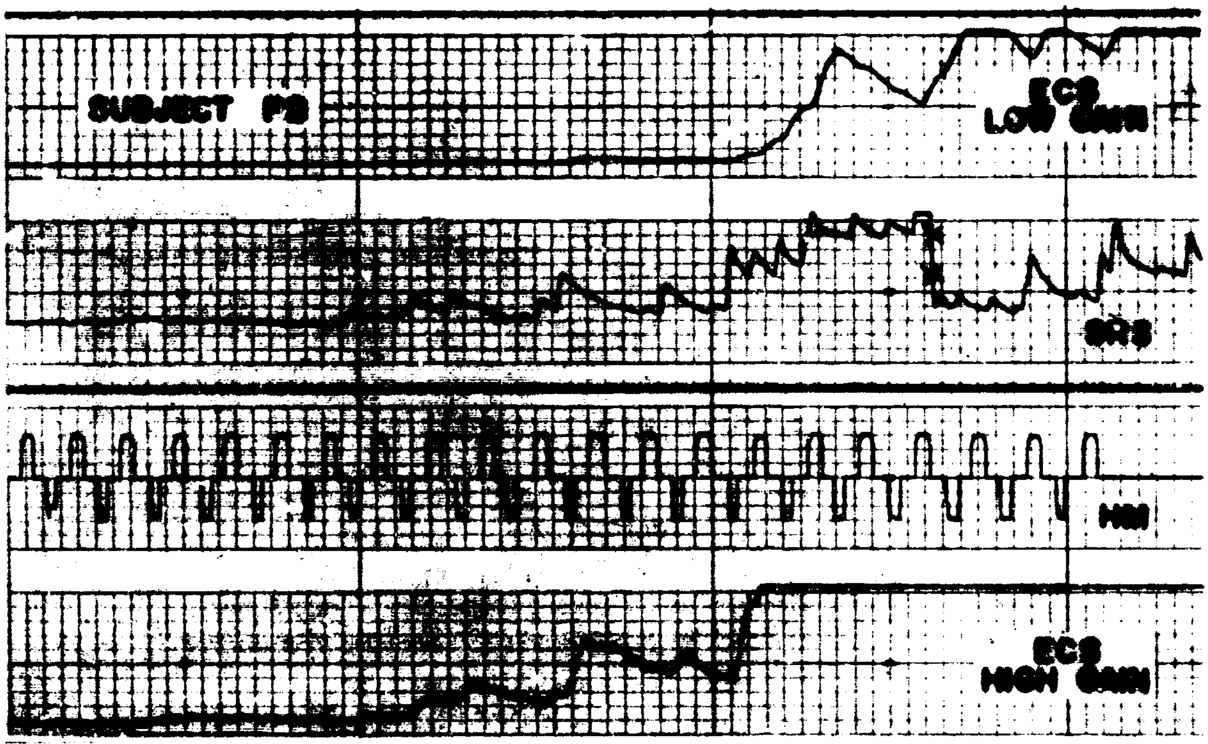

Figure 8

Typical sweat response from the dorsal hand during motion sickness. ECS: electrochemical sweat sensor. SRS: skin resistance sensor. HM: head movements. ECS high gain is 12.5 times the low gain. Paper speed 1 mm/sec.

For this particular example, motion sickness was induced by side-to-side head movements of the subject while he was on a chair rotating at constant velocity. The graph third from the top is a record of the head movements as detected by a head-movement counter worn by the subject.

Of note is the pulsatile nature of the sweat response, which has been described previously (4,11) and is seen with both the ECS and the SRS. The frequency of the pulsations is quite variable, with the time between peaks varying from 5 to 25 seconds in this particular case. This frequency range is representative of that seen in well over 100 responses from the dorsal hand recorded during motion sickness, and agrees with Nakayama and Takagi (11) who reported a range of 3 to 9 seconds in response to thermal stress. This is in contrast to the study by Custance (4) which showed pulsatile sweating in nonpalmar skin areas in response to thermal stress, with the duration between peaks generally greater than 1 minute.

In the example shown in Figure 8, there is a one-to-one relationship between the ECS pulsations and the SRS pulsations. The ECS response lags the SRS response by approximately 2 seconds. Since the ECS responds only to moisture at the skin surface, it is probably safe to conclude that, in this particular case, the pulsations seen in the SRS trace represent actual sweat expulsion into the sweat-gland duct and not presecretory activity.

Some authors (6,7,10,14,16,17) have suggested that presecretory activity in the eccrine sweat glands or activity in the epidermis is to a certain extent responsible for the palmar sweat response seen with the conventional GSR. Figure 9 represents a different pattern of response from that seen in Figure 8 and suggests that presecretory activity may also be detectable in nonpalmar areas. This trace illustrates the sweat response in a different subject during motion sickness. In this case pulsations can be seen in the SRS trace several minutes prior to the indication by the ECS that moisture is present at the skin surface. Note also that when the ECS does respond, there is a corresponding rise in the SRS response. It is suggested that the early pulsations seen in the SRS trace of Figure 9 represent presecretory activity while the later activity seen in both the SRS and ECS traces represents the actual expulsion of sweat through the sweat-gland duct and onto the skin surface.

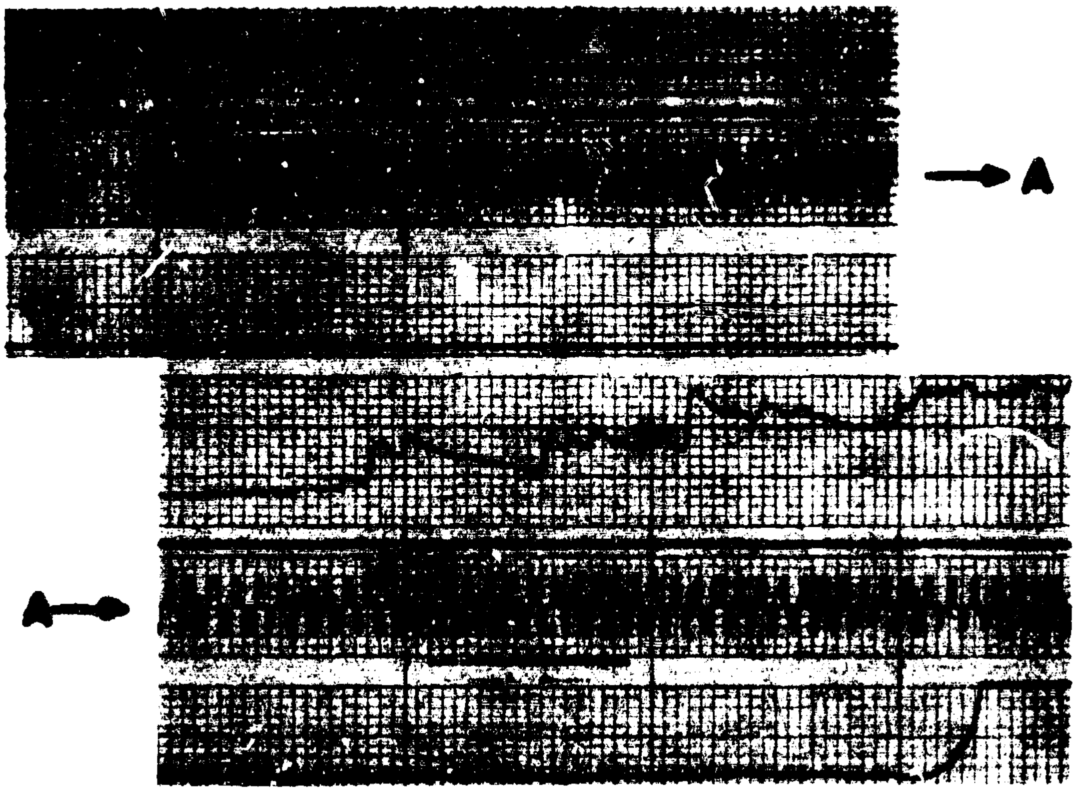

Figure 9

Sweat response from the dorsal hand during motion sickness. SRS response prior to ECS response suggests presecretory activity. A signifies upper and lower traces are continuous. Paper speed 1 mm/sec.

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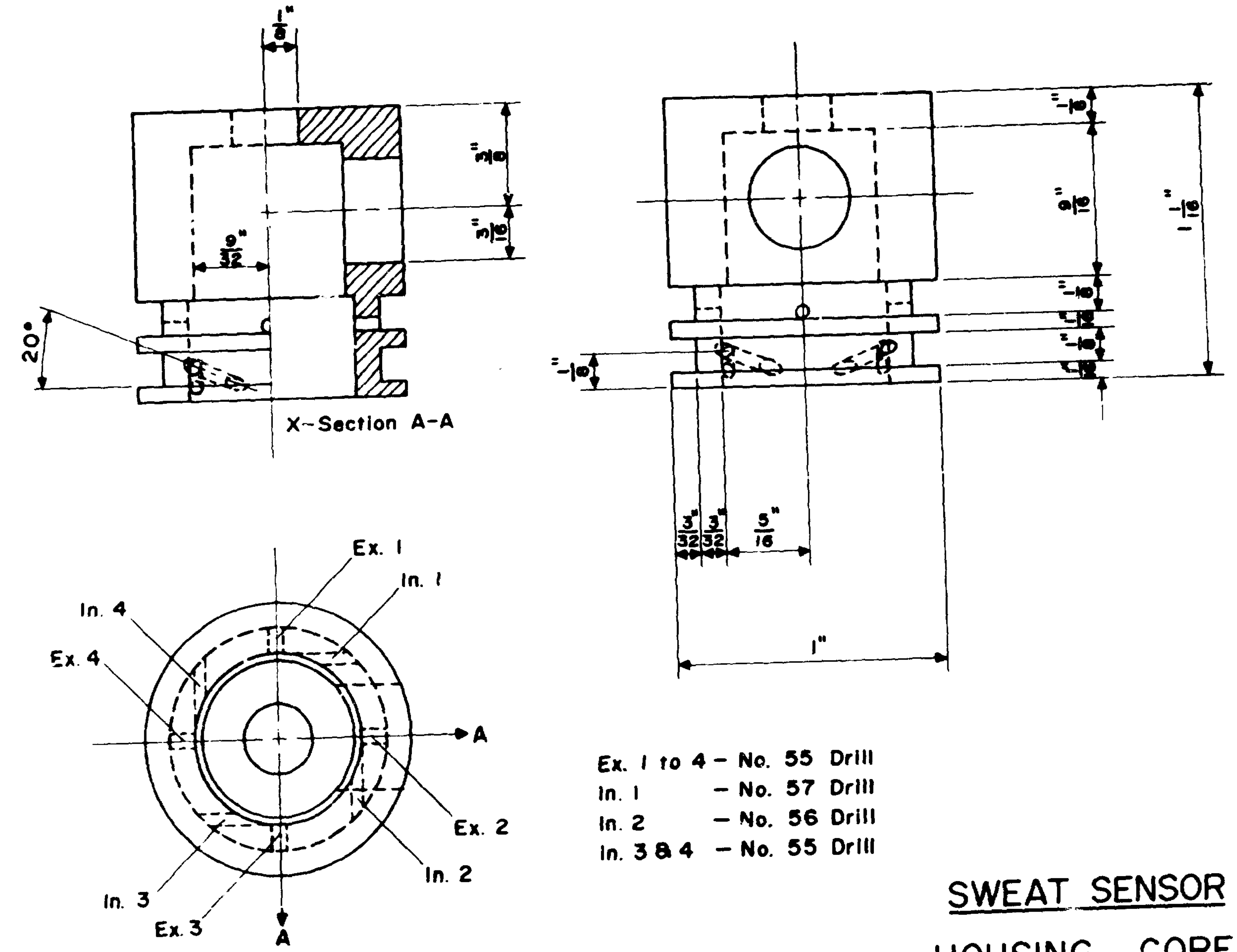
APPENDIX

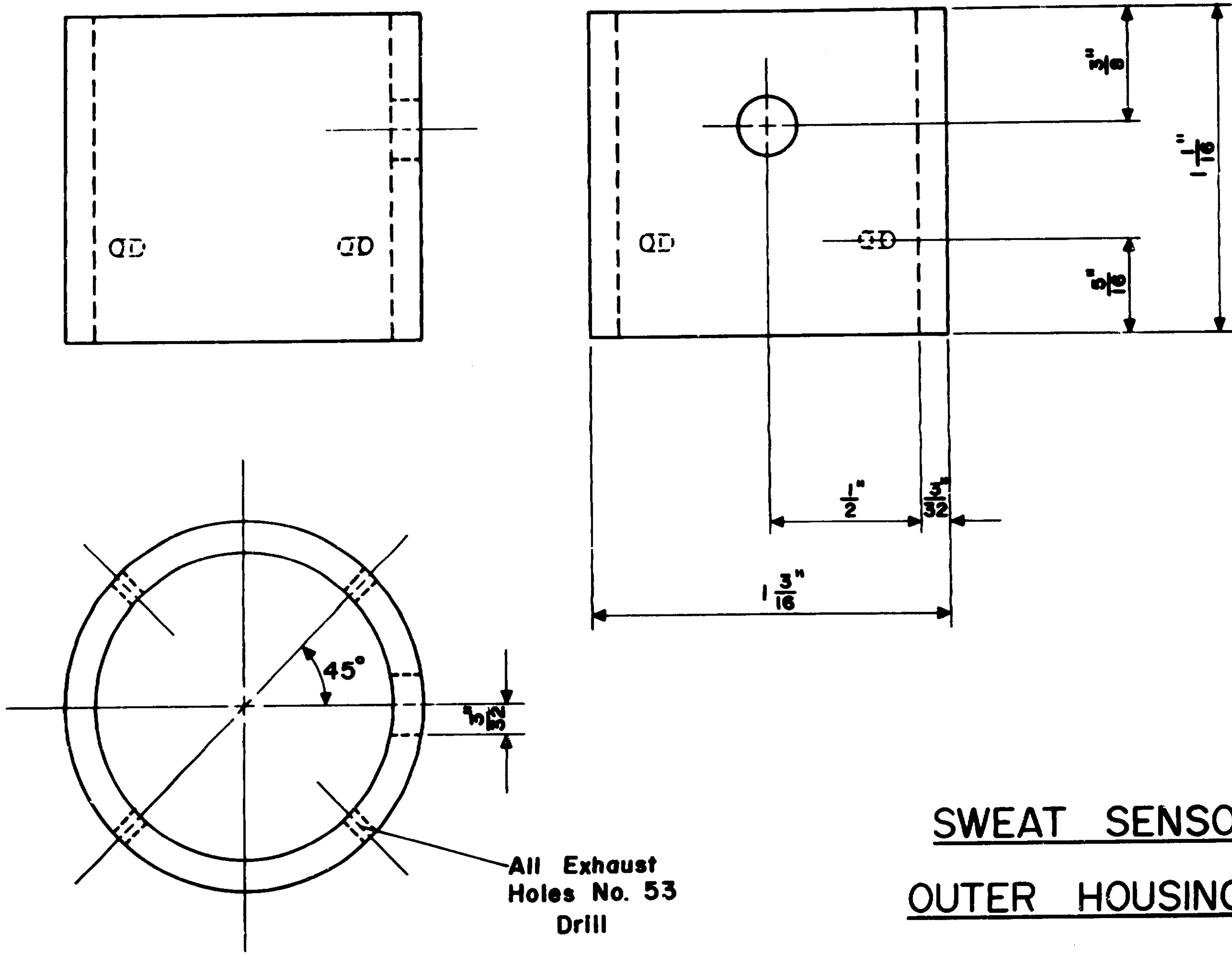
DETAIL DRAWINGS AND FABRICATION INSTRUCTIONS FOR SWEAT SENSOR



SWEAT SENSOR

HOUSING CORE

Figure 1A



SWEAT SENSOR

OUTER HOUSING

Figure 2A

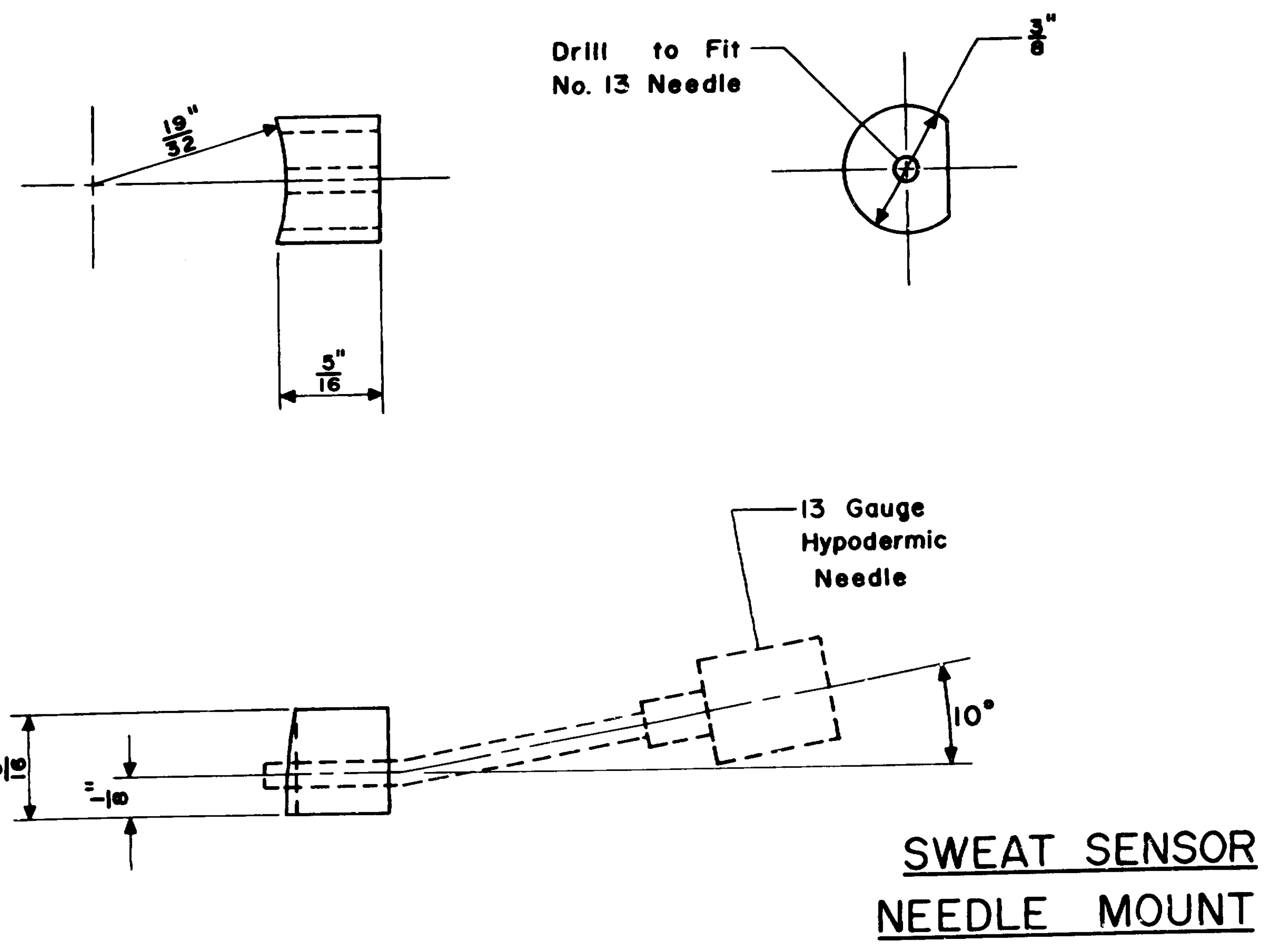
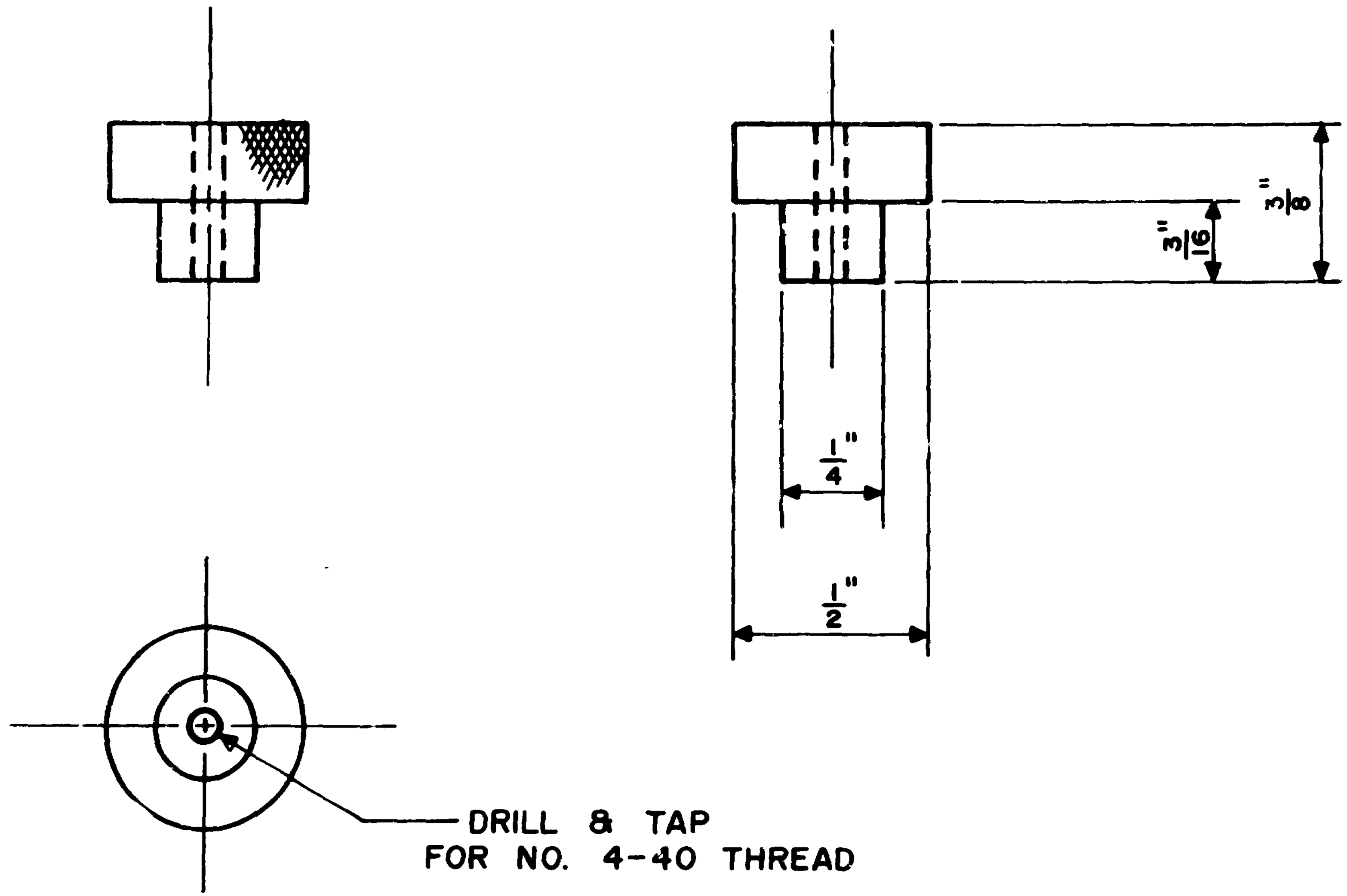

19"/32
5"/16
Drill to Fit No. 13 Needle
3"/8
13 Gauge Hypodermic Needle
10°
5"/16
1"/8
SWEAT SENSOR
NEEDLE MOUNT

Figure 3A



SENSING ELEMENT

HOLDING NUT

Figure 4A

CONSTRUCTION AND ASSEMBLY DETAILS

1. Materials: Sweat-sensor housing core - acrylic
   Sweat-sensor outer housing - acrylic
   Sweat-sensor needle mount - acrylic
   Sensor-element holding nut - aluminum

2. All sensor parts cemented and sealed with any standard acrylic cement (e.g. methylene chloride, ethylene dichloride, 1-1-2 trichlorethane) or epoxy cement.

3. Main intake port fabricated from no. 13 aluminum hypodermic needle and sealed in sweat-sensor needle mount by epoxy cement.

4. Sensing element constructed as per Ackermann. Use subminature phone jack for electrical connector.

5. No. 4-40-1/2" nylon screw cemented to back of sensing element (as per Figure 2 of text) by epoxy cement.

MOUNTING

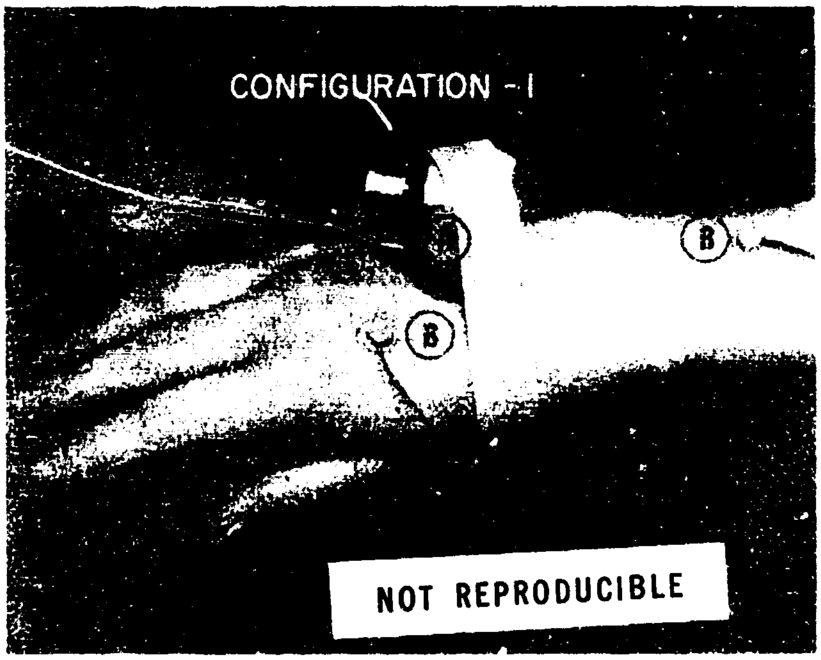


Figure 5A

Photograph of electrochemical sweat sensor marked A mounted on the dorsal hand. Sensor is held in place with masking tape.