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NCJ-00056

June 1960

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FOREWORD

These observations were authorized under Task 4C08-02-023-01, Basic and Applied Physiology. They were made between 20 March and 13 April 1959. This report was submitted for publication in March 1969.

Acknowledgement

The authors are indebted to the staff of the Aerosol Branch for making available to us the human volunteer subjects during exposures conducted by the Aerosol Branch, and for their observations confirming the exposures.

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DIGEST

During the BLACK MAGIC program of tests on the incapacitating agent CS, detailed observations of the breathing behavior of six human volunteer subjects were made by means of the remotely-controlled breath-recording system under development for the CARAMU program. Although the breathing patterns were disrupted by CS, adequate ventilation of the lungs was maintained, so that the incapacitation is attributed to the unpleasant sensations rather than to any degree of respiratory failure.

CONTENTS

BREATHING PATTERNS DURING HUMAN EXPOSURE TO CS

I. INTRODUCTION

During the spring of 1959 a large number of human volunteers were exposed to the riot control agent, CS, in the form of an aerosol generated under controlled conditions in a wind tunnel. The observers[1] concluded that the agent produced incapacitation by affecting the eyes, the respiratory tract, or both. They regard the symptoms referable to the respiratory tract as potentially the most capable of causing incapacitation. Accordingly, it became of interest to observe the breathing behavior. The availability of one unit of a self-contained, remotely-controlled breath-recording system, under development for estimating casualties from munitions (CARAMU), permitted us to make observations in a short series of exposures.

II. PROCEDURE

Of the four or five man entering the wind tunnel for an exposure, one man was equipped with the breath-recording device. The recorder was started by a radio signal and when an outside observer saw the cloud arrive he impressed by radio a signal mark on the record. To measure the duration of the exposure, a stop watch was started at the same time as the radio signal and stopped when the man left the wind tunnel. The concentration of CS was determined by members of the Aerosol Branch.

The device consists of (a) an air-flow transducer mounted in an oronasal mask of rubber sheet 0.020 inch thick attached to the skin with adhesive tape, (b) a recorder (figure 1, appendix) with enough magnetic tape to last 3 minutes and (c) a radio receiver and other electronic components. Items b and c were carried in a pack on the back (figure 2, appendix) with a shielded cable leading to the transducer. The equipment carried by the man weighed 10 pounds. A developmental prototype of the transducer has been described by Dahlke and Welkowitz.[2,3] The finished transducer is 2 inches in diameter and ½ inch thick and is illustrated elsewhere.[4] It consists of networks of strain-gage wire bonded to alternate sides of 8 flexible vanes attached to the circumference of the airway and projecting into the airway. When no air is moving, the airway is nearly closed; when air moves in either direction, the vanes bend, opening the airway and devorming the strain-gage wire. Since the gages form two arms of a bridge circuit, air movement produces an imbalance in the bridge. The arrangement of the gages compenstaes for thermoelectric effects and the connections are waterproofed to protect against condensation from the expired air. The output is nearly the same in either direction if the direction of air movement alternates as in breathing. The balance changes, however, if the transducer is subjected for very long to steady or intermittent flow in only one direction.

The output of the bridge enters a phase modulation circuit and is then subjected to pulse position modulation for recording on magnetic tape. The circuit and recorder are modifications by Dahlke and Welkowitz[2] of those described by Upham and Dranetz.[5] The tape transport mechanism is driven by a voltage-sensitive motor powered by a nickel-cadmium rechargeable battery. Successful operation depends on a delicate balance between the battery power and the resistance of the tape transport mechanism. Roughness in the tape transport or imbalance in the demodulator results in noise in the baseline of the final record. A decline in the battery voltage during a 3-minute run produces a shift in the baseline level and reduction in amplitude of the signal. For retrieval of information, the tape is played back. The output from the tape passes through a demodulator and is recorded on an oscillograph in the same manner as a conventional pneumotachogram. The remote control radio transmitter and receiver are of the type used with model airplanes.[3] The system is identified as the production prototype delivered by the contractor in December 1958.[6]

As shown in figure 3 (appendix), the resistance of the transducer to air movement was comparable to the inspiratory resistance of the M17 protective mask.[7] The transducer used in these experiments had a nearly linear calibration for steady air flows measured by Fisher-Porter rotameters (figure 3). The response of the transducer apart from the remainder of the tape recording system has been described elsewhere.[8] When the same breath was passed through the conventional screen pneumotachometer and the transducer in series, the response was comparable with respect to ability to follow sudden changes in air flow and the tidal volume of the breath. The transducer is too thin, however, to permit sufficient bending of the vanes to respond to instantaneous flows above 250 liters per minute.

The accuracy of the system was tested by comparing the volumes of several breaths during and after a brief run on the treadmill by a man wearing the transducer under an M9A1 protective mask. The canister was removed and the inlet was connected to a 120-liter recording spirometer with a scale factor of 0.1326 liter per millimeter of height of the bell. The transducer output was recorded on magnetic tape. In order to resolve the oscillations imposed on the record of instantaneous flow by the impact of the fect on the treadmill and the consequent shock to the column of air extending from the lungs out through the mask, a high speed of paper transport in the Sanborn oscillograph was required. This amounted to 266 centimeters per minute. Since the playback speed is double the recording speed, the Sanborn paper speed was equal to 133 centimeters per minute of breathing. The duration of the breaths as recorded on tape was verified by comparison with a simultaneous recording of mask pressure on another Sanborn oscillograph. The volumes of several breaths were measured by reading from the record the instantaneous flow for each millimeter of the time scale. The instantaneous flow is the product of the pen deflection and the calibration factor for the system, 10 liters per minute per millimeter of pen deflection. The sum of the instantaneous flows divided by 1330 millimeters per minute yields the volume of the breath in liters. In table 1 (appendix) the inspired volumes recorded by the spirometer and by the transducer are listed together with the volumes of the intervening expirations also recorded by the transducer.

Since so large an excess of inhalation over exhalation is unlikely, sources of error were considered. In order to follow the rapid changes in flow, a hot pen was required; this produced a wide trace at slow flows and made a precise setting of the baseline uncertain. Inspection of the record shows the baseline may have been 0.5 millimeter further on the inspired side than the line employed in reading the pen deflections. From the total number of readings, 323 for inspiration and 297 for expiration, it was calculated that the mean pen deflections were 5.1 millimeters for inspiration and 4.5 millimeters for expiration. Corrected for possible error in the baseline of this size and direction, the average pen deflections become 4.6 millimeters for inspiration and 5.0 millimeters for expiration, and the total volumes 11.2 liters for inspiration and 11.2 liters for expiration. Such a shift in the average pen deflection is in harmony with the fact that the inspiratory phase was longer than the expiratory phase. The difference between 11.2 and the spirometric total in tale 1 is not far from the 5 percent discrepancy between the spirometer and the rotameter used to calibrate the transducer. The volume collected in the spirometer is less by this much than the volume blown through the rotameter calculated from the rate indicated by the rotameter and the time of collection. This discussion does not exhause the possibilities for error in the portable breath-recording system but may indicate that it has sufficient accuracy for field use.

III. RESULTS

The records are illustrated in figures 4 and 6, appendix. A period of quiet breathing in the wind tunnel before the cloud arrived was followed by the exposure, and the subsequent recovery outside the wind tunnel. Deviations from the quiet breathing pattern as a result of the exposure consist of periods of no air movement (a) between inspiration and expiration, (b) between expiration and inspiration, and (c) during the expiratory phase. Expanded portions of the records appear in figures 5 and 7, appendix. A spike in the expiratory direction was impressed on the record by a radio signal to indicate the arrival of the cloud. This time is only an approximation, since the concentration edge of the cloud is not sharp; some aerosol is thought to reach the subjects before the visible wisps of cloud can be seen. The following information applies to the top record in figure 5. The exhalation following the signal appeared normal and a further 0.43 liter was inhaled out of the total of 0.59 liter in that breath before the first irregularity in breathing could be seen. A complex cough followed and, after inhaling a total of 0.93 liter more, the subject left the wind tunnel at B. In one inspiration the instantaneous flow rose from 0 to 200 liters per minute within 0.05 second. The various periods in which no air flow was recorded add up to about 5.8 seconds. The subject did not intentionally hold the breath as a device to prolong the exposure, perhaps because of the risk of taking in a large breath at the end of the hold.

Numerical data are listed in table 2, appendix. The concentration of CS in the aerosol cloud ranged from 5 to 150 micrograms per liter and the voluntary exposure times from 110 to 12 seconds. The total dose inhaled depended on the breathing during the exposure period so there was no close relation between concentration and dose. The changes in the breathing pattern as a result of exposure were the three types of interruption of breathing mentioned above plus the cough, but the quantitative aspect of the changes was quite varied from one exposure to another. The first detectable change in the breathing pattern came from 3 to 12 seconds after the arrival of the cloud, although in the exposure of BM no marked change in the breathing pattern was seen. In this case the subject had had considerable experience with the agent and entered the wind tunnel with the intention of maintaining a regular breathing pattern. The volume inhaled between the signal and the first respiratory response and the total inhaled during the exposure are listed to permit calculations of the doses inhaled. The times without breathing represent the sum of all the periods of zero flow observed during the exposure. In no case (except that of JC) was there a period long enough to suggest an intention to hold the breath. The total volume exhaled during the exposure was subtracted from the total volume inhaled. The difference indicates the amount by which the lungs were more filled, or less filled, at the end of the exposure than at the beginning. The differences were not greater in either direction than the volume of a large breath and so may be accounted for by the possibility that the respiratory cycle of inspiration and expiration was not completed during the exposure. Minute volumes based on complete cycles were calculated for the periods before and during exposure. They were less during than before exposure but all were greater than the expected value for a man standing at ease. The maximum instantaneous inspiratory flow rate was recorded for each exposure and ranged from 50 liters per minute for relatively quiet breathing in BM to 250 liters per minute in LT. The number of coughs were counted during exposure and recovery; the triple exhalation in figure 7 (top record) was counted as one cough. Although coughing and dose were not systematically ralated, it is worth noting that LT and S had both doses and numbers of coughs that were far greater than those seen in the other exposures.

Table 2 also includes the case of JC who was provided with a gas mask and instructed to put it on when he became aware of the CS. His breathing record during exposure is shown in figure 8, appendix. The cloud arrived at A during a normal exhalation of 1.77 liters. After inhaling only 0.17 liter the subject halted his breathing, opened the mask carrier at M and proceeded to don the mask. At C he exhaled 0.52 liter to clear the mask and resumed breathing. He was unable to breathe normally and after inhaling a further 2.07 liters he left the wind tunnel at B.

IV. DISCUSSION

In the large group of subjects described by Gutentag, Hart, Owens and Punte[1] from which our six subjects were drawn, the first symptom of CS exposure related to the respiratory tract was "burning" which began in the throat and progressed downward with or without coughing. As the exposure continued, this burning became painful and was rapidly followed by a "constricting" sensation throughout the chest. This latter system was associated with incapacitation for several minutes. Panic usually accompanied and accentuated this sympton and persons so affected appeared unable to inhale or exhale. Usually there was mild to moderate burning of the nose and throat. This was more irritating than incapacitating and disappeared readily in fresh air.

In the normal pneumotachograms of Fleisch,[9] inspiration and expiration follow each other without an intervening period of zero flow. In a few normal subjects, Proctor and Hardy[10] observed a pause of from 0.1 to 0.4 second following expiration. In our records the longest period of apnea was 4 seconds except for the longer voluntary breathhold of JC included in the masking reaction. Shorter pauses between the phases of the respiratory cycle were quite common, however. Although there may have been some constriction of the airway, there was no reason to suppose the airway was blocked except momentarily as a part of the cough reflex.[11] The peak instantaneous flows in the coughs recorded here were not as high as the flows of from 500 to 700 liters per minute recorded by Whittenberger and Mead,[12] in part because of the limited range of the transducer.

The textbook description of the respiratory response to irritants is exemplified by the following statement of Schmidt.[13] "A sneeze is elicited by irritation of the mucous membrane of the nose, a cough by irritation of the respiratory passages beyond the nose." He goes on to state that during anesthesia, irritation of the upper air passages causes apnea. This reflex is actually present in the conscious subject but is overshadowed by the violent expiratory effort that is absent in the unconscious state.

According to literature cited in reviews by Ranson[14] and Aviado and Schmidt,[15] the efidence regarding the sneeze is derived from experiments on anesthetized animals, usually the rabbit. Search of the literature has so far revealed no pneumotachogram of a human sneeze. In our records we saw nothing that looked like a frank sneeze, which we suppose would be characterized by a large slow inspiration followed by a sharp expiration, probably not as explosive as a cough. Sneezing was common, however, among observers exposed to small concentrations of CS at some distance from the exposure chamber. The impression of the pauses between inspiration and expiration in subject FC is that they were largely involuntary. The gasping behavior subjectively resembled what happens before a sneeze, but the irritation was more pronounced than that usually leading to a sneeze.

Electrical stimulation of the tracheobronchial mucosa accomplished during bronchoscopy indicates that the linings of the trachea and bronchi are sensitive and that pain results. Morton _et al_[16] have charted the areas in which the pain was felt. Pain arising from the bronchial tree was referred to the homolateral anterior chest within 2 to 4 centimeters of the sternum, or to the anterior cervical region within 2 centimeters of the midline. Pain of tracheal origin was felt in the midline anteriorly, at sites extending from the larynx to the xyphoid process. Pain of bronchial origin was usually abolished by a unilateral vagus section on the same side[17] and the cough reflex elicited by mechanical and electrical stimulation onthe same side of the bronchial tree was also abolished.[18]

For the particle size (3 microns) employed on the 4 days of these tests, data cited by Punte[19] indicate that as much as three-fourths of the aerosol would be retained in the upper respiratory tract. For particle sizes of 1 micron and below, virtually all the material retained would be in the lower part of the tract. The smaller particle size was employed in some of the tests with the larger group of subjects.[1] It appears that either pain or coughing may result from stimulation of the tracheobranchial mucosa with either CS aerosol or an electric shock but we do not know the parameters of the stimulus that determine which result will occur. In view of the distribution of the particle size in these exposures, we cannot exclude the likelihood of penetration of some CS into the lower respiratory tract and may with Punte (personal communication) attribute to this the burning and constricting sensation of the chest. On the basis of the doses in table 2, it appears likely that a massive penetration is required to produce a bout of coughing. The statement of Schmidt,[13] quoted above, suggests that the brief periods of apnea in our record result from strong stimulation in the nose. Much weaker stimulation with CS may be required to produce a sneeze.

Although CS produced great distortion of the pneumotachogram, the data for minute volume in table 2 make it clear that adequate ventilation of the lungs was maintained during these exposures. The large minute volume before exposure is interpreted as emotional hyperventilation.

The behavior of the man who donned the protective mask after the cloud reached him needs to be considered, for the respiratory flowmeter and its connecting cable could easily impair the seal of a hastily donned mask. However, the exposure time of JC was within the range of the untrained group provided with masks who were exposed to about the same concentration, described by Gutentag, Hart, Owens and Punte.[1] In a personal communication, Mr. A. L. West stated that a large breath was required to clear the mask after donning in order to render tolerable a long period of exposure to CS. If a good seal to the face could be obtained over the flowmeter, some quantitative studies on this point might be appropriate.

V. SUMMARY

1. At a concentration of 5 micrograms per liter one trained subject was able to maintain a normal breathing patern for 110 seconds.

2. At higher concentrations the breathing pattern consisted of short inspiratory or expiratory gasps separated by short and variable periods of zero air flow.

3. Coughing was conspicuous in only two exposures with the highest total inhaled doses.

4. Ventilation of the lungs was maintained during the exposures at a normal or greater than normal rate.

5. Voluntary breath holding was not employed as a means of prolonging the exposure.

VI. CONCLUSION

Although the breathing patterns were disrupted by CS, adequate ventilation of the lungs was maintained, so that the incapacitation is attributed to the unpleasant sensations rather than to any degree of of respiratory failure.

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APPENDIX

TABLES AND GRAPHS

TABLE 1

COMPARISON OF TIDAL VOLUMES RECORDED WITH A SPIROMETER AND WITH THE PORTABLE TAPE RECORDING SYSTEM*

Breath	Condition	Time	Inspired Volume		Expired Volume
			Spirometer	Tape	Tape
		1330 mm / min	liters	liters	liters
1	Run	2			1.19
1	Run	42	1.19	1.48	
2	Run	85			1.27
2	Run	130	1.46	1.71	
3	Run	178			1.44
3	Run	228	1.46	1.69	
4	Run	274			1.44
4	Run	321	1.33	1.68	
5	Run	363			1.31
5	Run	404	1.19	1.26	
6	Stand	440			1.03
6	Stand	469	2.52	2.83	
7	Stand	535			2.32
7	Stand	598	1.59	1.69	
8	Stand	660			
Total					

* Date were obtained in connection with another series of experiments on 3 March 1959 from subject F running at 9 miles per hour up a 12 per cent grade and include the first two breaths in recovery. (Craig, F. N., and Cummings, E. G. Breathing in Brief Exercise. 1960 manuscript).

TABLE 2

SUMMARY OF EXPOSURES TO CS

Date, 1960	4/3	3/30	4/6	3/30	4/6	4/3	3/31
Subject	BM	FC	LT	FC	K	S	JC**
Previous exposures	+	-	+	+	-	+	-
Concentration of CS, micrograms per liter*	5	12	15	64	80	150	175
Duration of exposure, seconds	110	24	61	15	12	12	27
Total dose inhaled, micrograms	101	55	451	129	184	450	-
Respiratory response time, seconds	-	5.2	11.6	4.2	4.6	4.9	2.6
Volume inhaled before response, liters	-	1.4	13.3	1.1	1.6	3.0	0.2
Time without breathing, seconds	0	9.2	12.0	5.8	8.2	4.5	19.1
Total volume inspired, liters	20.1	4.6	30.1	2.0	2.3	3.0	2.3
Inspiration less expiration, liters	-	1.1	1.9	-1.3	1.5	-2.2	0.7
Maximum inspiratory flow, liters per minute	50	95	250	200	70	160	150
Minute volume before exposure, liters per minute	21.7	13.1	23.5	17.4	20.7	34.4	17.3
Minute Volume during exposure, liters per minute	11.0	16.5	29.6	8.0	11.5	15.0	5.1
Number of coughs	0	4	15	2	0	16	0

* The mass median diameter in these exposures was 3 microns.
** JC donned a protective mask when the cloud arrived.