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Long-term exposure to electric fields

A cross-sectional epidemiologic investigation of occupationally exposed workers in high-voltage substations

by BENGT KNAVE, M.D.,¹ FRANCESCO GAMBERALE, Ph.D.,¹ SVEN BERGSTRÖM, E.E.,¹ ELISABETH BIRKE, M.Sc.,² ANDERS IREGREN, M.Sc.,¹ BIRGITTA KOLMODIN-HEDMAN, M.D.,¹ and ARNE WENNBERG, M.D.³

KNAVE, B., GAMBERALE, F., BERGSTRÖM, S., BIRKE, E., IREGREN A., KOLMODIN-HEDMAN, B. and WENNBERG, A. Long-term exposure to electric fields: A cross-sectional epidemiologic investigation of occupationally exposed workers in high-voltage substations. *Scand. j. work environ. & health* 5 (1979) 115—125. In the present epidemiologic study, 53 workers with a long-term (more than five years) exposure to the electric field of 400 kV substations were examined and compared with a matched reference group of 53 nonexposed workers from the same power companies. Matching variables included age, geographic location and employment time. The aim of the study was to investigate the possibility of persistent, chronic health effects in the exposed group as a consequence of exposure. The investigation included the nervous system (neurasthenic symptoms, psychological tests, electroencephalography), the cardiovascular system (symptoms, blood pressure, electrocardiography), and the blood (hemoglobin, red blood cells, reticulocytes, white blood cells including differential count, thrombocytes, sedimentation rate). Fertility was also assessed. The results showed no differences between the exposed and reference groups as a consequence of the long-term exposure to the electric fields. The groups differed, however, in that the exposed group had (a) consistently better results on the psychological performance tests, (b) a fewer number of children, especially boys, and (c) somewhat higher education. The differences in test results were due to the higher education among the exposed. The difference in number of children was also thought to be related to factors other than exposure since it was found to be present already 10—15 years before the work in 400 kV substations began.

Key words: blood, cardiovascular system, fertility, electromagnetic fields, epidemiologic study, health examination, nervous system, substation workers.

It is well known that exposure to electric fields can cause functional changes in biologic systems (21). A human being who

enters an electric field may find that the hair on his skin vibrates (so-called pilo-erection). Spark discharges may occur between skin and clothing or between skin and grounded objects ("electric shocks"). The field intensity threshold for the emergence of such effects is fairly well known (8). Persons working within electric fields can find the discharges disturbing.

In addition to the effects mentioned, functional disturbances have been reported in the nervous, circulatory and gastrointestinal systems of Russian workers in

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high-voltage substations (1, 2, 3, 9, 25, 26, 27, 28) and in experimental studies on volunteers (17). Subjective complaints included fatigue, headache, dizziness, impaired memory, nausea, loss of strength in the limbs, respiratory difficulties, increased nervousness, sleep disturbances, and reduced libido. Effects that were recorded objectively were changes in the number of blood cells, reduced systolic blood pressure, sinus arrhythmia and sinus tachycardia in electrocardiograms (ECGs), and desynchronized alpha activity and focal activations in electroencephalograms (EEGs). Impaired performance was also reported for vigilance and reaction time tests. The Russian studies covered about 500 workers at 500 kV, 400 kV, 330 kV, and 220 kV substations. The aforementioned effects were associated with work at 400 and 500 kV substations. Work in 220 kV substations was not found to pose any health hazards.

These results from substation workers were supported in a Spanish study on nine workers who suffered headache, dizziness, fatigue and nausea after they had begun work in a 400 kV substation (10).

Results of studies on substation workers in other countries do not agree with the Russian data, however. Singewald et al. (30) carried out health examinations of ten linemen over a period of nine years and did not find any symptoms of nervous disorder or changes in the ECG, blood, circulatory system, lung function, kidney function, sperm production, or in vision or hearing. Strumza (32) examined over 500 persons living inside and outside the immediate vicinity of 200/400 kV transmission lines. The frequency of physician consultations, the use of medications, and the medical histories did not differ between the two groups, one living within an area of less than 25 m from the transmission lines and the other residing in an area 125 m away from the lines. In another study, no differences were found between a group of 84 high-voltage linemen and substation workers and a group of 94 low-voltage linemen with regard to a routine physical examination, chest radiographs, ophthalmoscopy, ECGs, and blood tests (22).

The results of the health examinations, then, do not agree. The same is true with regard to experimental studies on humans (11, 12, 13, 14, 34) and animals (5, 7, 16,

18, 19, 20, 23, 24, 29, 31, 33, 34). As long as 25 years ago, subjectively experienced changes in taste and hearing, as well as "pains in the nerves," were reported at a field strength of 100 kV/m (14). In a laboratory experiment of more recent times, nine volunteers showed a brief, slight increase in pulse and blood pressure, as well as changes in GSR (galvanic skin response), upon exposure to a field strength as low as 3 kV/m (34). In contrast, no effects related to exposure to electric fields of 15 kV/m could be noted in ECGs, EEGs, pulse, blood pressure, reaction time, or blood cells of ten test subjects (12). No effects on the ECG, the EEG, blood pressure, or reaction time were found for six subjects exposed to 20 kV/m (11), nor did any effects show up on a psychological test or in the form of subjective symptoms when 20 subjects were exposed to 100 kV/m (13).

It is obvious that the results available, including those from field studies of exposed workers and those from human and animal experiments, are highly contradictory. Therefore, it is impossible to make any statement about health hazards in connection with work at substations. In fact, the effects described could not be considered to have been documented with certainty, and the individual-related exposure to electric fields was not surveyed. It was therefore deemed urgent to record individual exposure, with epidemiologic methods, to investigate whether long-term exposure to electric fields affects the nervous and circulatory systems or the blood and fertility status of high-voltage substation workers in Sweden. Sweden began as early as 1952 to use transmission system voltages of 400 kV.

WORKPLACE AND WORK CONDITIONS

The examined workers were primarily employees of the Swedish State Power Board, but some worked for the privately owned South Swedish Power Company. The Swedish State Power Board has about 11,000 employees, about 5,000 of whom are

engaged in the Operation and Administration Department. Organizationally, the administration and operation facilities are divided geographically into five different administrative areas. The South Swedish Company has 2,000 employees, 1,600 of whom are engaged in power supply and distribution.

The personnel who work in operation and administration can be divided into two main groups, *substation workers* and *low-voltage distribution workers*. The latter group has a comparatively insignificant exposure to electric fields.

High-voltage substation workers

Substation workers in 400 kV plants can be divided into two subgroups, namely, station personnel and circuit breaker personnel.

Station personnel are placed permanently at one or several neighboring substations, where they carry out the everyday tasks of maintenance and operation. The work is organized differently within the different administrative units. At some of the substations, a work rotation system is used, while at others the personnel are divided into a maintenance group and an operation group. Operation is monitored by the person who has the so-called "check-up" week. A "check-up" week, which occurs about once a month per worker, calls for making readings from the instruments, writing reports, recording statistics and making inspection rounds throughout the substation. If the substation is unmanned at night, the person is on duty at home where the news of an alarm may reach him via telephone. Making the rounds entails a visual inspection of the equipment throughout the entire plant at the same time that certain readings are being taken from the instruments. The rounds last between 1.5 to 2.0 h and take place two or three times per week. Other common tasks in the substation are switching, correcting defects, cleaning the breakers, painting, changing light bulbs, mowing the lawn, shoveling snow, etc.

The *circuit breaker personnel* are not stationed at any special substation. Instead, they work within an entire administrative

area. They often work away from home since the administrative areas are large. Their main tasks are the inspection and maintenance of breakers and disconnecting switches. To a smaller degree, they work with tap changers on transformers. Maintenance measures are carried out on breakers and disconnecting switches according to a certain routine. The work time for, e.g., making revisions in a breaker varies between 2 and 7 d, depending upon the type of breaker involved.

Low-voltage distribution workers

The reference group was selected from this personnel category. The low-voltage distribution personnel work chiefly with a voltage of 220/380 V. Occasionally tasks occur involving exposure to system voltage of up to 20 kV. The work, which can generally be done without travel away from home, includes, e.g., the changing of insulator chains and conductors, the digging of cable trenches, inspection and maintenance of cable terminal cabinets, construction of new transmission lines and stations, and meter-reading at the consumers.

Exposure to electric fields

Exposures were determined in 20 substations in different parts of the country. The subsequent evaluation was made with respect to (a) field strengths at a height of 1.8 m in the substations and (b) exposure during different parts of the work routines.

Field strengths

Field intensities at a height of 1.8 m in the substations were measured with a field intensity meter, which measures the undisturbed field (19). As an example, it may be mentioned that so-called high-built substations may have large areas with field intensities up to 10–15 kV/m, while so-called low-built substations may have substantial areas with field intensities of about 20 kV/m.

Table 1. Percentage of time spent in electric fields of different strengths during inspection rounds and everyday work in 400 kV substations.

Work	Exposure (kV/m)			
	0—5	5—10	10—15	15—20
Inspection rounds	60	37	2	1
Everyday work	34	61	4.8	0.2

Table 2. Percentage of time spent in electric fields of different strengths during two types of breaker work in 400 kV substations.

Work	Exposure (kV/m)			
	0—5	5—10	10—15	15—20
Revision	66	0	18	16
Testing	95	5	0	0

ladders or scaffoldings. These put the worker on the same level as the breaker, i.e., at a height of 6—8 m. The field intensity at these places is considerably different from the intensities measured at ground level because the grounded breakers provide partial shielding there. The degree of exposure in breaker work depends, then, a great deal upon how often the worker is on an elevated level beside the breakers and how close he is to the live parts. Table 2 shows the average exposure levels for two different breaker operations in a 400 kV substation, namely, revision and testing. The table shows that the exposure is considerably higher in the former than in the latter. This difference stems from the fact that revisions are made to a substantial degree while the worker is in an elevated position, whereas testing is carried out almost entirely on the ground.

Exposure during different parts of the work routine

The exposure was recorded as the actual work routines were being carried out. The person being tested had a portable dosimeter which registered the number of seconds he spent in field strengths above three given levels.

Station personnel. Table 1 shows the average exposure levels for the person making the rounds (visual inspection and instrument readings) and for the person doing general work involving large areas of the substation, e.g., mowing the lawn. The table shows that the exposure for carrying out the general tasks at the substation is somewhat higher than that for making the rounds. This difference stems primarily from the fact that the person making the rounds carries out the instrument readings and inspection routines as he stands beside grounded cable racks which shield him from the electric field.

Circuit breaker personnel. A substantial part of the work involved in the repair or revision of breakers is performed from

EXAMINED GROUPS

Selection

During the spring of 1974, the various regional administrations were informed about the planned study, and personal information was collected on potential subjects. Information was obtained on 178 high-voltage substation workers for the exposed group and on 350 low-voltage distribution workers for the reference group. For each substation worker, a referent was chosen who was as similar as possible to the exposed person with respect to geographic location, age, duration of employment at the Swedish State Power Board/South Swedish Power Company, and also, whenever possible, with respect to duration of employment in electric production in general.

A special questionnaire concerning the period of employment in 400 kV plants was sent to all of the 178 exposed persons. The exposed group was chosen so as to include substation workers (station personnel and circuit breaker personnel) who had

worked more than five years in 400 kV plants as of the beginning of 1975, a total of 68 persons. During the fall of 1975, a questionnaire concerning education, marital status, number of children, housing conditions, dietary habits, use of tobacco and alcoholic beverages, medical history, history of accidents, and use of medications was distributed. The questionnaire was filled out by all but two of the exposed and two of the referents.

The medical examinations were carried out in different parts of the country during the period between March and October 1976. A total of four of the exposed and eight of the referents did not undergo the examination. The reasons for their dropping out are shown in table 3.

Furthermore, it turned out, during subsequent investigations, that three of the referents had been exposed, and they were therefore also excluded. Every time an exposed or a referent dropped out, his respective referent or exposed match was also excluded. The final material thus came to consist of 53 matched pairs.

The country was divided geographically into three parts: northern, central and southern Sweden. The test subjects and referents were distributed in the following manner: 13 pairs from northern Sweden (Norrbotten and Central Norrland regional administrations), 27 pairs from central Sweden (Älvkarleby and Motala regional administrations), and 13 pairs from southern Sweden (Trollhättan regional administration and South Swedish Power Company).

Exposed group — reference group

Age. At the beginning of 1975, the average age was 46.0 years for the exposed group and 45.8 years for the reference group. The age distribution is given in table 4.

Length of employment. At the beginning of 1975, the average length of employment was 21.0 years in the exposed group and 15.6 years in the reference group. It should be noted that a number of the persons in the reference group had previously been employed by smaller companies, which had later been taken over by the Swedish State Power Board.

Education. Table 5 shows that, on the average, the exposed group had a higher education than the reference group. By a basic education beyond the compulsory education in Sweden (previously elementary school up to and including the sixth grade; now elementary school plus junior high school up to and including the ninth grade) is meant advanced studies at a vocational school, an apprenticeship school, or the like. No one in either of the groups had a high school (college preparatory)

Table 3. Reason for drop-out from the original groups selected for examination.

Reason	Exposed group (N = 68)	Reference group (N = 68)
Illness	1	5
Retirement	1	
Refusal	1	2
Change of workplace	1	1
Total	4	8

Table 4. Age distribution of the examined groups.

Age group (years)	Exposed group (N = 53)	Reference group (N = 53)
< 29	1	1
30—39	15	14
40—49	13	15
50—59	21	21
> 60	3	2

Table 5. Educational background of the examined groups.

Education	Exposed group (N = 53)	Reference group (N = 53)
Basic education beyond compulsory education in Sweden	23	9
Courses sponsored by Swedish State Power Board/South Swedish Power Company	36	12

Table 6. Living conditions during the work week.

Living conditions	Exposed group (N = 53)	Reference group (N = 53)
Live at home	37	45
Live away from home	11	4
Sometimes at home and sometimes away	5	3

education. With regard to employer-sponsored courses, only those exceeding one month were included.

Special living conditions. Table 6 shows that the exposed group, on the average, was away from home more often during the week than the reference group was.

Use of alcohol and tobacco. No differences in alcohol or tobacco consumption were found between the groups. The average alcohol consumption was 164 g/month in the exposed group and 161 g/month in the reference group. (In the calculations, the content of alcohol was assumed to be 32 g/l for beer, 120 g/l for wine, and 334 g/l for hard liquor.) The average tobacco consumption was 55 g/week in the exposed group and 53 g/week in the reference group.

METHODS OF INVESTIGATION

Nervous system

Standardized interviews. Data on the prevalence of neurasthenic symptoms, anxiety and depression, frequency of physician consultations due to such symptoms, and data on confounding and effect-modifying factors were collected with the use of a modified version of a standardized interview worked out at a Scandinavian meeting on health hazards connected with the use of solvents (4). The interview has been

used by us in other epidemiologic investigations (15).

Psychological tests. Eight performance tests (6, 15) were carried out individually by each subject. The subjects were studied in such an order as to obtain comparability between the exposed and reference groups with regard to time of day and day of week for the examination. The tests were performed by each subject in the following order: *simple RT* (RT = reaction time), *memory test 1* (recognition), *manual dexterity* (Santa Ana), *RT Addition, tapping, perceptual speed* (Bourdon-Wiersma), *memory test 2* (reproduction), and *matrices*.

Electroencephalography. The EEGs were recorded by means of an 8-channel Siemens-Elema EEG machine. The subjects were awake in a semireclined position with their eyes closed during the recording. The electrodes were placed according to the 10/20 system. The paper recordings were evaluated in the following way: (a) They were visually examined according to a routine clinical procedure. (b) From each EEG a typical 10-s section (8 channels) was selected. These sections from each and every one of the persons examined (2×53) were ranked without any knowledge of which subjects they belonged to. This ranking procedure was carried out so that the EEGs showing a distinct, stable alpha activity were given low ranks, while higher ranks were assigned to EEGs with a decreasing amount of rhythmic activity. This procedure was recently described in an epidemiologic study on jet fuel-exposed industrial workers (15).

Circulatory system

The examination included standardized interviews on symptoms and signs, ECG (standard leads from extremities and six chest leads), standardized blood pressure measurements (on the left arm after 15 min in a supine position). Codings and interpretations of the results were made by a physician without knowledge of whether the subject belonged to the exposed or nonexposed group. The ECGs were classified according to the Minnesota Code.

Blood

The blood tests included analyses of hemoglobin, hematocrit, number of red blood cells, reticulocytes, white blood cells (with differential counts), thrombocytes and sedimentation rate.

Fertility

Fertility was assessed from the data collected on the number of children born, their sexes, and the dates of birth in relation to exposure, i.e., if they occurred before or after the dates on which the fathers began to work at high-voltage substations.

RESULTS

Nervous system

Standardized interviews. No differences were found between the exposed and reference groups with regard to responses to

questions on neurasthenia or confounding and effect modifying factors. For instance, 16 persons in the exposed group and 17 of the referents responded "yes, often" to one or several of the neurasthenia questions of the interview.

Psychological tests. As can be seen in table 7, the average performance of the exposed group was, except for the Simple RT test, consistently better than that of the reference group. In five out of ten comparisons the differences between the groups were statistically significant ($p < 0.05$).

When the results were subjected to further analysis, it became apparent that the differences in performance between the two groups could be ascribed almost entirely to the differences in educational background. On one hand, it was found that the differences in performance on the various tests were very small when exposed workers were compared with non-exposed workers of the same educational background, and, on the other, the differences were greatest when workers with different educational backgrounds were compared irrespective of whether they be-

Table 7. Mean values and standard deviations of the performance on psychological tests for the exposed and reference groups and p-values from the two-sided significance testing of the differences between the mean values.

Test	Exposed group		Reference group		P
	Mean	SD	Mean	SD	
Simple RT (ms)	282.00	40.00	282.00	36.00	< 0.50
Memory test 1 (number correct)	30.26	3.72	27.07	4.94	< 0.001
Manual dexterity (number of turns correct)					
One hand	92.36	9.13	86.32	11.50	< 0.01
Both hands	31.23	5.27	29.29	6.32	< 0.10
RT addition (s)	3.29	0.81	2.84	0.97	< 0.02
Tapping (number of presses)	412.00	57.00	398.00	48.00	< 0.20
Perceptual speed (s)	12.84	2.84	13.98	2.87	< 0.05
Memory test 2					
Criterion 1 ^a	5.47	0.76	5.20	1.14	< 0.15
Criterion 2 ^b	55.04	9.31	48.86	12.45	< 0.01
Matrices (number correct)	11.55	4.36	10.32	4.15	< 0.15

^a Criterion 1: number of correctly reproduced combinations.

^b Criterion 2: number of correctly reproduced elements.

Fig. 1 A—C. Cumulative number of children (A), boys (B) and girls (C) of the exposed (solid line) and reference groups (dotted line) over time. "0" on the time axis denotes real and hypothetical "beginning of exposure" of the exposed and reference groups, respectively. Insets: statistical fourfold tables.

longed to the exposed or the nonexposed group.

Electroencephalography. A visual inspection of the EEGs showed 11 of the exposed and 14 of the referents to have slight or moderate deviations from the

normal pattern, mainly focal abnormalities. There was no difference between the groups when the EEGs were ranked with regard to rhythmic alpha activity.

Circulatory system

As mentioned earlier, the history of signs and symptoms from the heart was recorded according to a standardized interview/questionnaire, and the ECG results were classified according to the Minnesota Code. In the exposed group, 36 persons were therefore classified as normal versus 30 in the reference group. No statistically significant differences were found between the exposed and referents with respect to the number of persons with various heart symptoms.

The number of persons with hypertension totaled 8 in the exposed group and 11 in the reference group. The systolic and diastolic blood pressure was, on the average, of the same order of magnitude in the exposed group (142/92) and in the control group (145/94).

Blood

The results of the blood analyses did not reveal a systematic difference between the exposed and reference groups.

Fertility

The fertility in the exposed and reference groups was assessed from data collected on the number and birth dates of children (boys/girls) of the examined workers. In the exposed group children were born both before and after their fathers began to work in high-voltage substations, i.e., before and after the start of exposure to electric fields. In order to make comparisons with the reference group possible, we assigned each of the matched referents a hypothetical "start year for exposure" which agreed with that of the relevant worker in the exposed group.

Fig. 1 A shows the cumulative number of childbirths per year up to the beginning

of 1975. The year that exposure began is indicated with "0" on the time axis. The diagram and the fourfold table within the diagram show that a total of 79 children were born in the exposed group versus 116 in the referent group. This difference is statistically significant ($\chi^2 = 7.02$; $p = 0.008$).

It appears from the diagram that the difference between the exposed and referent groups (79 and 116 children, respectively) arose successively, and it started long before the start of exposure. There is thus no statistically significant relationship between exposure and the number of children born in the two groups ($\chi^2 = 0.48$; $p = 0.488$).

Fig. 1 B and C show the cumulative number of boys and girls, respectively. The diagrams show that the difference between the two groups as to number of children has mainly to do with male births (38 and 65 boys, respectively, $\chi^2 = 7.08$; $p = 0.008$). The difference with regard to female births is less pronounced and not statistically significant (41 and 51 girls, respectively, $\chi^2 = 1.09$; $p = 0.296$). No relationship between exposure and number of childbirths could be found when the material was divided according to sex (boys/girls) ($\chi^2 = 1.55$; $p = 0.213$ and $\chi^2 = 0.02$; $p = 0.888$, respectively).

DISCUSSION

In the present comparative investigation the exposed workers, on the average, were found to have (a) fewer children, especially boys, (b) better performance results on tests of psychomotor and cognitive functions, and (c) a higher education than the referents.

The exposed and referent groups were not equivalent, thus, as regards education, which is probably the explanation for the differences in the psychological test results between the groups. The group differences in education and test results also indicate that the groups were not fully comparable as to socioeconomic and personality variables. Against such a background the ob-

served difference in number of childbirths cannot be regarded as surprising — all the more as this difference developed and existed long before the beginning of exposure and was relatively constant during the entire length of the observation time (fig. 1). It should be pointed out that the differences between the groups with respect to the ratio boys/girls cannot be attributed to differences in background factors. The possibility cannot be excluded that work in electric fields played some role in this result. However, we consider it unlikely in light of the overall assessment of the results of the study. It should also be pointed out that, if work in substations, contrary to what seems to be the case in this study, had affected the number of childbirths and/or the ratio boys/girls, the effect could be ascribed, hypothetically, just as well to other important aspects of the work, such as stress, awareness of accident risks, discomfort caused by fear of discharges, etc.

The results of the present study show no evidence for the development of persistent, chronic health effects in high-voltage substation workers as a consequence of exposure to electric fields. Thus the Russian and Spanish findings (see Introduction) were not confirmed by the present investigation. There are many possible reasons for the discrepancy in results, but it should be recognized that in most of the earlier investigations on substation workers there were severe limitations, e.g., the use of too few subjects and/or the lack of a reference group.

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