



Neurobehavioral and Cognitive Performances of Children Exposed to Low-Dose Radiation in the Chernobyl Accident

The Israeli Chernobyl Health Effects Study

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Exposure to low levels of ionizing radiation after the Chernobyl accident in the Ukraine could potentially have influenced the neurobehavioral and cognitive performances of exposed children. A cohort study of adolescents who were children at the time of the accident and who subsequently emigrated to Israel was conducted in 1998–2001. A total of 1,629 children (59% of all 2,769 invited) were included in the study (41% from higher contamination areas, 25% from lower contamination areas, 34% from noncontaminated areas). Mean scores of the Raven Standard Progressive Matrices Test were highest in children in all exposure groups whose parents had a high level of education. No overall relation was found between the cognitive function scores of the child and his/her putative radiation exposure level. Conners' test T scores did not differ significantly by level of exposure. Mothers of all exposure groups who were pregnant at the time of the accident gave their children significantly higher Conners' test scores than did those who were not pregnant. Scores for hyperactivity and attention-deficit/hyperactivity disorder were significantly higher among those who were in utero at the time of the accident. These results do not show differences of neurobehavioral or cognitive performance in exposed versus nonexposed children. There is a possible behavioral effect among offspring of pregnant mothers or mothers of very young children in all exposure levels.

accidents; radiation; child; cognition; health; neurobehavioral manifestations; radiation

Abbreviation: ADHD, attention-deficit/hyperactivity disorder.

The accident at the Chernobyl Nuclear Power Plant in the Ukraine in 1986 was the largest nuclear reactor accident ever reported. The accident caused the dispersion of radioactive fallout over large areas, which exposed millions of people to different amounts of radiation (1).

Although a lot of attention was first paid to the physical health consequences of the radiation-exposed groups, concern was also raised regarding the neurodevelopmental sequelae in those who were exposed to radiation in utero or at a young age. It could be hypothesized that prenatal and early childhood irradiation of the brain could lead to neurobehavioral dysfunction (2).

Studies of the survivors of the atomic bombs in Hiroshima and Nagasaki, Japan, indicated that the fetal brain is most susceptible to high doses of ionizing irradiation for 8–15 weeks after conception. Fetal exposure to high doses of radiation increased the risk of mental retardation, small head size, subsequent seizures, and poor performance on conventional tests of intelligence (3, 4).

After the Chernobyl accident, an excess of thyroid cancers among exposed children was reported and, more recently, some genetic changes of unclear importance have also been described in children possibly influenced by the Chernobyl radiation exposure (5, 6). Psychological stress, anxiety, and fear, especially in adults, were reported in several studies

after the Chernobyl accident (7–12). Studies of the impact of the Three Mile Island accident showed in one study greater psychological distress among women who were pregnant or had young children (13) but showed in another study no such effect (14). Further, young children living near the Three Mile Island reactor did not differ from children living next to another reactor in their prevalence of behavioral problems (15).

In addition to several hundred thousand individuals who were relocated within the former Soviet Union after the disaster, hundreds of thousands more left the country. Many of them emigrated to Israel. Israeli immigrants from the Chernobyl region manifested high levels of anxiety and concern about radiation. Additionally, they showed inaccurate preconceptions about the health risk of chronic radiation exposure and sought extensive health care for what they feared would be long-term illnesses caused by the Chernobyl Nuclear Power Plant disaster (16, 17). No differences were found in the cognitive and neuropsychological functioning of evacuated children who were in utero or up to 15 months of age at the time of the accident when they were compared with their classmates in Kiev (18).

The present study, among others, was designed to evaluate possible influences of the exposure to ionizing radiation after the Chernobyl accident on the neurobehavioral and cognitive performances of Israeli immigrants who were young children at the time of the accident.

MATERIALS AND METHODS

Study population

All children aged up to 4 years (including in utero) at the time of the accident who emigrated to Israel from the Gomel (highly exposed) region and a convenience sample of immigrant children from the Mogilev and Kiev (mildly exposed) regions and from the (nonexposed) cities of Moscow and St. Petersburg, as well as other unexposed areas of Belarus, were invited to participate in the study. Exposure levels of the various areas were determined according to geographic cesium contamination maps of the International Atomic Energy Agency. Altogether, 1,629 children (58.8 percent of 2,769 children sampled and invited, whose mailing addresses were confirmed from a selected cohort of 4,319 children) who emigrated to Israel between 1989 and 2000 were included. Of these, 667 (41 percent) children came from areas with high contamination, 408 (25 percent) came from areas of low contamination, and 554 (34 percent) came from noncontaminated areas. Compliance rates of samples of children with an identified address are as follows: 65 percent for children from Moscow-St. Petersburg, 62.2 percent for children from other Belarusian cities, 60.2 percent for children from Mogilev, 57.0 percent for children from Gomel, and 54.9 percent for children from Kiev.

The area of origin in the former Soviet Union was defined as the settlement of origin in their home countries recorded by the Ministry of Immigrant Absorption in Israel upon registration of their families for immigration. This indicator was validated by information collected during the participant's interview. Final assignment to area of exposure was

based on the true origin of the child and not on the information appearing in the official documents.

All the children were invited, with their mothers, to the CHS National Cancer Control Center at the Carmel Medical Center in Haifa, Israel. The Israeli Chernobyl Health Effects Study took place during the years 1998–2001. Participating children were thus aged 12–18 years at the time of the study.

Data collection

After signing an informed consent form, the child's mother was interviewed by trained Russian-speaking interviewers who used a standardized questionnaire. The questionnaire sought demographic data, residential and personal radiation exposure (for dose estimation) data, and information on exposure to various risk factors during the relevant pregnancy, disease status, and health behavior patterns of the relevant child. All children undertook a cognitive test and a questionnaire evaluating their behavior. A complete physical examination, self-reported puberty staging according to the Tanner scale, and venous blood tests including hematology and thyroid panels were also conducted but are not discussed in this report. Assessment of attention-deficit/hyperactivity disorder (ADHD) was carried out using the short Conners' Rating Scales-Revised for children and their mothers (19). Nonverbal intelligence was examined by the Raven Standard Progressive Matrices Test (20). This test is not language dependent and, therefore, functions well in a new immigrant population.

Measurement of cognitive ability. Cognitive ability of the children was measured by using the Raven Standard Progressive Matrices Test (1996 edition) (20). This nonverbal intelligence test was selected because the study population of immigrant children had diverse levels of knowledge of Hebrew. The test consists of 60 diagrammatic puzzles. Each puzzle has one part missing, which the child has to fill in with one of the options provided after proper explanation by the test administrator. No time limit was set for completion of the test.

The child's score was calculated as the total number of problems solved correctly. A table of percentile norms (20, table SPM 14) was used to interpret the scores. These norms enabled us to compare the performances of children in the various exposure groups.

Assessment of attention. The assessment of ADHD was carried out by using Conners' Rating Scales-Revised. These scales are a comprehensive assessment of psychopathology and problem behaviors of children and adolescents.

The Adolescent Self-report Scales and the Parent Rating Scales (which relate to the child's behavior) (19) were chosen for this study. The short forms (27-item questionnaire) yielded scores on four parameters (appearing in both the adolescent and parent questionnaires): oppositional problems, cognitive problems, hyperactivity, and risk of ADHD. Children were provided with a Hebrew version of the questionnaire, and their mothers were provided with a Russian version. Conners' Rating Scales-Revised are available in only English, Spanish, and French. Because we needed a Hebrew version for the children and a Russian version for their mothers, the questionnaires were translated into

TABLE 1. Child population, by residency at time of accident, Israeli Chernobyl Health Effects Study, 1998–2001

Residential area	Level of cesium 137 (Ci/km ²)*	No. of children approached	Participating children		Children in utero at time of accident	
			No.	%	No.	%
Gomel region, Belarus, and other exposed areas in Belarus and the Ukraine	1–40	1,169	667†	57.0	98	15
Mogilev region, Belarus	<1	216	130	60.2	14	11
Kiev region, the Ukraine	<1	506	278	54.9	48	17
Other regions in Belarus	≤0.1	598	372	62.0	72	19
Cities of Moscow and St. Petersburg, Russia	≤0.1	280	182	65.0	38	21
Total		2,769	1,629		270	16.6

* According to an International Atomic Energy Agency map, 1989.

† A total of 26 children (3.9%) lived in very high contaminated areas (15–40 Ci/km²).

Hebrew and Russian and then translated back into English to validate the translation. The crude scores of the Conners' test were translated into T scores, which are age and gender specific. T scores of 65 or more usually indicate a significant clinical problem, while T scores between 56 and 64 warn of a possible problem.

Statistical analyses

Statistical analyses using SPSS/PC, version 10.07 (SPSS, Inc., Chicago, Illinois), software included comparison of different exposure groups (all groups, or highest exposure group vs. others) by means of analysis of variance. After studying individual scores, we used models that adjusted the test scores for the following potential effect modifiers, identified in the univariate analysis: child's gender, birth order, number of siblings, family status (two parents or single parent), timing of exposure (in utero vs. not in utero), and parent's level of education.

RESULTS

Of the 2,769 children approached, 1,629 (58.8 percent) participated. Of these, 270 (16.6 percent) were in utero at the time of the accident (table 1). The mean age of the study participants at the time of the accident in 1986 was 1.48 (standard deviation, 1.31) years. Of the participating children, 48 percent were females, and 52 percent were males.

No major differences were found in the ages at the time of the accident ($p = 0.62$) and in the gender distribution ($p = 0.88$) of the children as related to the different exposure groups. Most children (69 percent) had one sibling, 21 percent had no siblings, and 10 percent had two or more siblings. Single-parent families comprised 20 percent of all study families. None of the participating children suffered from significant mental or physical handicaps at the time of the study.

The age of the participating children at the time of the study ranged from 12 to 18 years. About a fourth of the children were aged 12–13 years at the time of the test, 45 percent were aged 14–15 years, and 31 percent were aged 16–18 years.

The exposure groups differed significantly in the level of education of their parents. Higher levels of education for both parents were noted in residents of the Moscow-St. Petersburg group, followed by residents of Kiev and Minsk (low- or no-exposure group), and were lowest in members of the high-exposure groups (table 2).

Cognitive assessment by the Raven Standard Progressive Matrices Test

Mean scores (percentiles) of the Raven Standard Progressive Matrices Test were highest in children in all exposure groups whose parents had a high level of education. The mean scores of the matrices test, adjusted for parent's level of education, differed significantly ($p < 0.0001$), although the difference did not correspond to the level of radiation exposure (table 3). No other variable was found to significantly influence the results. Children who were in utero at the time of the accident did not score differently from older children in the same exposure area.

Attention assessment by the Conners' test

The children's test results for the Conners' test did not show any significant difference by radiation exposure level, after controlling for gender, birth order, number of siblings, family status, and parent's level of education. Rates of all exposure groups were within a normal range (score of less than 50) (table 4).

Significant differences in the oppositional and hyperactivity subscale scores of the mother's test, but not in the subscale scores for cognitive function and ADHD, were noticed between the different exposure groups. However,

TABLE 2. Level of parent's education, by exposure group, Israeli Chernobyl Health Effects Study, 1998–2001

Exposure group	Mother's level of education						Father's level of education					
	9–11 years		Technical		High		9–11 years		Technical		High	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Gomel and other exposed areas	91	14	295	44	281	42	174	26	232	35	256	39
Mogilev	8	6	57	44	65	50	27	21	55	42	48	37
Kiev	24	9	99	36	154	56	46	17	92	33	138	50
Other Belarus	26	7	132	36	214	58	51	14	112	30	205	56
Moscow and St. Petersburg	1	0.5	33	18	148	81	7	4	28	16	142	80
Total	150	9	616	38	862	53	305	19	519	32	789	49

these differences were unrelated to the degree of radiation exposure (highly exposed areas compared with all other exposure areas or a comparison of all five exposure levels separately). Most scores were within the normal range (score of less than 56), while the other scores were within the borderline range (score of 56–60) (table 4). Mothers with a high level of education rated their children significantly lower (on all scales except for the oppositional subscale) than did less educated mothers.

Mothers' scores were significantly higher ($p \leq 0.001$ for each of the subscales) than their children's scores. This was true for each of the five residence groups. The subjective assessment of the children's health status by their mothers was found to correlate negatively with the mother's score on the Conners' test. In all radiation exposure groups, mothers who rated their children highest (good to excellent health status) scored lowest on the Conners' test ($p < 0.001$).

Mothers from all radiation exposure groups who were pregnant at the time of the accident rated their children with significantly higher Conners' test scores in three of four categories than did those who were not pregnant. The scores, however, were mostly in the normal range (table 5).

A negative correlation was found between the scores of the Raven matrices and the scores of Conners' test (mother's or child's score). All correlation coefficients were very low but statistically significant. The highest correlation coefficients were found between the Raven score and Conners' test score for the cognitive subscale ($r = 0.2$ for mothers, $r = 0.1$ for children; $p < 0.0001$ for both).

DISCUSSION

No relation was found between exposure to radiation (proxy estimated by location of residence at the time of the accident) and performance in tests measuring neurobehavioral and cognitive performance. This result may either reflect a true lack of relation between radiation and behavioral performance or may be the result of one of numerous biases. This study was a large, population-based study in which a whole cohort of children emigrating from exposed areas in the former Soviet Union was recruited and included a convenience sample of children from nonexposed areas as well. The sampling frame came from governmental registration files and is believed to have a high validity and lack of

TABLE 3. Matrices' mean scores, by parent's level of education, Israeli Chernobyl Health Effects Study, 1998–2001

	Gomel	Mogilev	Kiev	Other Belarus	Moscow and St. Petersburg
Mother's education					
9–11 years	50 (29)*	52 (23)	61 (30)	46 (25)	
Technical school	54 (29)	49 (29)	57 (31)	58 (27)	60 (33)
University	67 (27)	61 (29)	76 (21)	69 (27)	78 (24)
Father's education					
9–11 years	52 (27)	46 (28)	63 (29)	54 (29)	52 (30)
Technical school	56 (30)	57 (29)	63 (28)	58 (27)	58 (31)
University	66 (28)	57 (30)	74 (24)	69 (26)	78 (24)
Total†	57 (29)	52 (28)	64 (29)	58 (30)	64 (30)

* Numbers in parentheses, standard deviation.

† Adjusted for mother's education.

TABLE 4. Conners' mean scores adjusted for mother's education, Israeli Chernobyl Health Effects Study, 1998–2001

	Gomel	Mogilev	Kiev	Other Belarus	Moscow and St. Petersburg
Child's scores					
Oppositional	48 (6)*	48 (7)	48 (5)	48 (7)	49 (6)
Cognitive	47 (7)	48 (8)	47 (7)	46 (6)	47 (7)
Hyperactivity	46 (7)	46 (7)	45 (7)	45 (7)	45 (7)
ADHD†	47 (8)	48 (9)	46 (7)	47 (7)	47 (7)
Mother's scores					
Oppositional	53 (10)	55 (12)	54 (10)	55 (10)	58 (11)
Cognitive	51 (8)	52 (8)	52 (7)	52 (8)	53 (8)
Hyperactivity	57 (13)	61 (16)	58 (14)	58 (13)	61 (13)
ADHD	51 (8)	52 (9)	52 (8)	52 (7)	54 (8)

* Numbers in parentheses, standard deviation.

† ADHD, attention-deficit/hyperactivity disorder.

selection bias. Compliance in this study was about 60 percent and was nondifferentially distributed among the various exposure groups. This, most probably, reflects a nonattendance that is not disease status related. If sick children were more apt to participate in this study, and if disease in these children was related to radiation exposure, then the data would be biased against the null. Because we did not find a relation between residence in areas affected by the Chernobyl accident and the degree of neurobehavioral or cognitive performance in our study population, we assume that no such bias occurred. In addition, the health status of the participating children was not found to differ between the cases and the controls in our series. Another possible bias is a misclassification bias in which children from seemingly exposed areas would be counted as nonexposed and vice versa. We tested the residence registration in the sampling frame and found it to correlate fully with the actual place of residence in 1986. A more serious question is whether residence in Gomel truly corresponds with high radiation exposure. Data from the former Soviet Union and from maps produced by the International Atomic Energy Agency several years after the accident have pointed at the Gomel region (or oblast) as the area with the highest contamination level outside the 30-km zone. Nevertheless, it is believed that urban dwellers as a group were exposed to lower radia-

tion levels than were rural dwellers. Jews in the former Soviet Union were mostly urban dwellers. This fact, coupled with evidence that the Chernobyl accident as a whole was a low-radiation-exposure event, could lead to studying and comparing groups that do not differ enough between themselves to show an increased risk, if such risk actually exists. No good measure of individual exposure to radiation is available.

Other findings in the study may indirectly validate the study results. The educational level of the parents was found, as expected, to be a strong positive predictor of performance. Good correlations between cognitive parameters in both tests and higher Conners' test scores of mothers versus their children correspond to the current knowledge in this field.

Interestingly, the neurobehavioral assessment of ADHD showed that mothers who were pregnant at the time of the accident scored their children with significantly higher scores than did nonpregnant women for their children. This was shown without any relation to exposure. Children's assessment scores, in the hyperactivity and the ADHD index, were significantly higher among those who were in utero at the time of the accident. This too was unrelated to exposure level.

Our results may suggest that mothers who were pregnant or had very young children at the time of the accident,

TABLE 5. Mean item score in Conners' test, by pregnancy status at time of accident, Israeli Chernobyl Health Effects Study, 1998–2001

Conners' test item	Pregnant (n = 270)	Not pregnant (n = 1,346)	p value
A (oppositional)	55.23 (10.28)*	53.77 (10.00)	0.029
B (cognitive problems)	51.61 (7.60)	50.81 (7.65)	0.119
C (hyperactivity)	56.92 (13.72)	56.82 (13.44)	0.002
D (risk of ADHD†)	52.44 (7.80)	51.36 (7.74)	0.036

* Numbers in parentheses, standard deviation.

† ADHD, attention-deficit/hyperactivity disorder.

regardless of their location in the former Soviet Union, had higher levels of anxiety and fear of the radiation. This might stem from lack of information and inaccurate preconceptions about the exact magnitude and spatial distribution of radiation. Such a sense of fear might either distort their perception or, alternatively, have been transmitted to their children who showed higher hyperactivity and ADHD index scores among the younger ages.

Similar results were found by Ginzburg (7), who reported high levels of anxiety and stress among adults from contaminated and noncontaminated villages. Nearly half of this study population, regardless of the true level of exposure, were unsure if they had a radiation-related illness. Two other studies from the Chernobyl area reported a high risk of psychiatric disorders among women with children under the age of 18 years residing in the exposed areas (21, 22). A study on the psychological effects of the Three Mile Island accident showed that women who were pregnant or had young children experienced the greatest psychological distress after the accident (13). The trauma brought on by the Chernobyl accident, experienced by mothers, was reflected in another study in their perceptions of their children's well being, particularly somatic symptoms. This anxiety, however, was not transmitted to the children themselves (8).

Two previous studies of the Chernobyl accident suggested lower cognitive performance among children exposed prenatally when compared with nonexposed children (2, 23). One of these studies (2) included evacuated children who were described as having been significantly more exposed than our study population. The second study (23) related to prenatally exposed children only, and it was based on very small numbers of children. Furthermore, these studies did not control for possible confounders (mainly, level of parent's education) as did our study, which did not demonstrate a similar lower performance. It is possible that emigration to a new place, remote from the irradiated area, played a role in lowering the anxiety level in the family.

We could not evaluate what, if any, influence the site of residence in Israel had. Moreover, we could also not determine if the level of education received by these children in Israel had an effect. However, because of Israel's mandatory-education law, it is highly likely that all these young children received formal education in Israeli schools. Given the small size of Israel and given that most of our participants came from one of nine cities in the country, it is unlikely that residence in Israel biased our results.

In a comparison of the cognitive and neuropsychological functioning of children who were between in utero and up to 15 months of age at the time of the Chernobyl disaster and who were evacuated to Kiev and their Kiev school classmates, no difference in performance was found (18).

Self-assessment of the child's health by the mothers was, as expected, negatively correlated with the attention assessment scores of the child. Health self-assessment has been found in many studies to correlate positively with physical health status (24).

In conclusion, the results of our large, population-based study of children who had been exposed to low-dose ionizing radiation do not show differences in neurobehavioral or cognitive performance compared with results of

nonexposed children. Thus, low-radiation events probably do not result in deviations in neurobehavioral and cognitive performance. Lower neurobehavioral performance of children who were in utero or young at the time of the accident, in all exposure groups, may possibly hint at a broader, country-wide, Chernobyl-related effect resulting in increased levels of anxiety in the pregnant mothers or mothers of very young children in the former Soviet Union.

Attention should be paid by agencies caring for relevant former Soviet Union populations to the possible effects of the anxiety of their subjects on the behavioral and cognitive functioning of the children. Providing validated information with regard to the true health effects of the Chernobyl accident may help to lower the level of anxiety.

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