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Original Article

Occupational Characteristics of Semiconductor Workers with Cancer and Rare Diseases Registered with a Workers' Compensation Program in Korea

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ABSTRACT

Background: The aim of this study was to describe the types of diseases that developed in semiconductor workers who have registered with the Korea Workers' Compensation and Welfare Service (KWCWS) and to identify potential common occupational characteristics by the type of claimed disease.
Methods: A total of 55 semiconductor workers with cancer or rare diseases who claimed to the KWCWS were compared based on their work characteristics and types of claimed diseases. Leukemia, non-Hodgkin lymphoma, and aplastic anemia were grouped into lymphohematopoietic (LHP) disorder.
Results: Leukemia (n = 14) and breast cancer (n = 10) were the most common complaints, followed by brain cancer (n = 6), aplastic anemia (n = 6), and non-Hodgkin lymphoma (n = 4). LHP disorders (n = 24) accounted for 43%. Sixty percent (n = 33) of registered workers (n = 55) were found to have been employed before 2000. Seventy-six percent (n = 42) of registered workers and 79% (n = 19) among the registered workers with LHP (n = 24) were found to be diagnosed at a relatively young age, ≤40 years. A total of 18 workers among the registered semiconductor workers were finally determined to deserve compensation for occupational disease by either the KWCWS (n = 10) or the administrative court (n = 8). Eleven fabrication workers who were compensated responded as having handled wafers smaller than eight inches in size. Eight among the 18 workers compensated (44 %) were found to have ever worked at etching operations.
Conclusion: The distribution of cancer and rare diseases among registered semiconductor workers was closely related to the manufacturing era before 2005, ≤8 inches of wafer size handled, exposure to clean rooms of fabrication and chip assembly operations, and etching operations.

1. Introduction

Controversy over the causes of semiconductor workers developing leukemia and a range of rare diseases has been growing since a young female former worker at a wafer fabrication (fab) operation died of leukemia in 2007. Her case was denied by the Korea Workers' Compensation and Welfare Service (KWCWS), but was later awarded compensation as an occupational disease by the administrative court.

Over the past decade, the speculation that semiconductor operations and the related working environments and jobs, especially those around before 2000s, may be harmful to workers has not been clearly examined. A number of former semiconductor workers have continued to claim that their chronic diseases, especially various types of cancer and rare disease, were associated with a

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semiconductor operation or job that they performed. No study has assessed the characteristics of jobs and diseases of semiconductor workers who had registered with the KWCWS to seek compensation.

The aims of this study are to describe the types of diseases that developed in semiconductor workers who registered with the KWCWS and to identify potential common occupational characteristics by the type of claimed disease.

2. Materials and methods

2.1. Overview of the national procedures for compensating occupational disease

The procedure for the receipt of compensation as an occupational disease for workers who assume that their disease may be caused by a job or work environment in which they were involved is shown in Fig. 1. In South Korea, any worker who develops a disease may claim to the KWCWS to seek compensation for it as an occupational disease. Such workers are required to submit an accident report to the KWCWS. This report includes basic information such as employment duration, name of the company of employment, type of process, type of job performed, and type of disease developed. According to the type of disease claimed, further investigation was conducted by a designated organization. Respiratory disease cases, including lung cancer, are investigated by the Occupational Lung Diseases Institute under the KWCWS. The investigation of workers who developed other cancers and rare diseases is generally conducted by the Occupational Safety and Health Research Institute. Occupational health professionals from these institutes generally visit the company, investigate the recorded documentation, and interview both employers and claimant

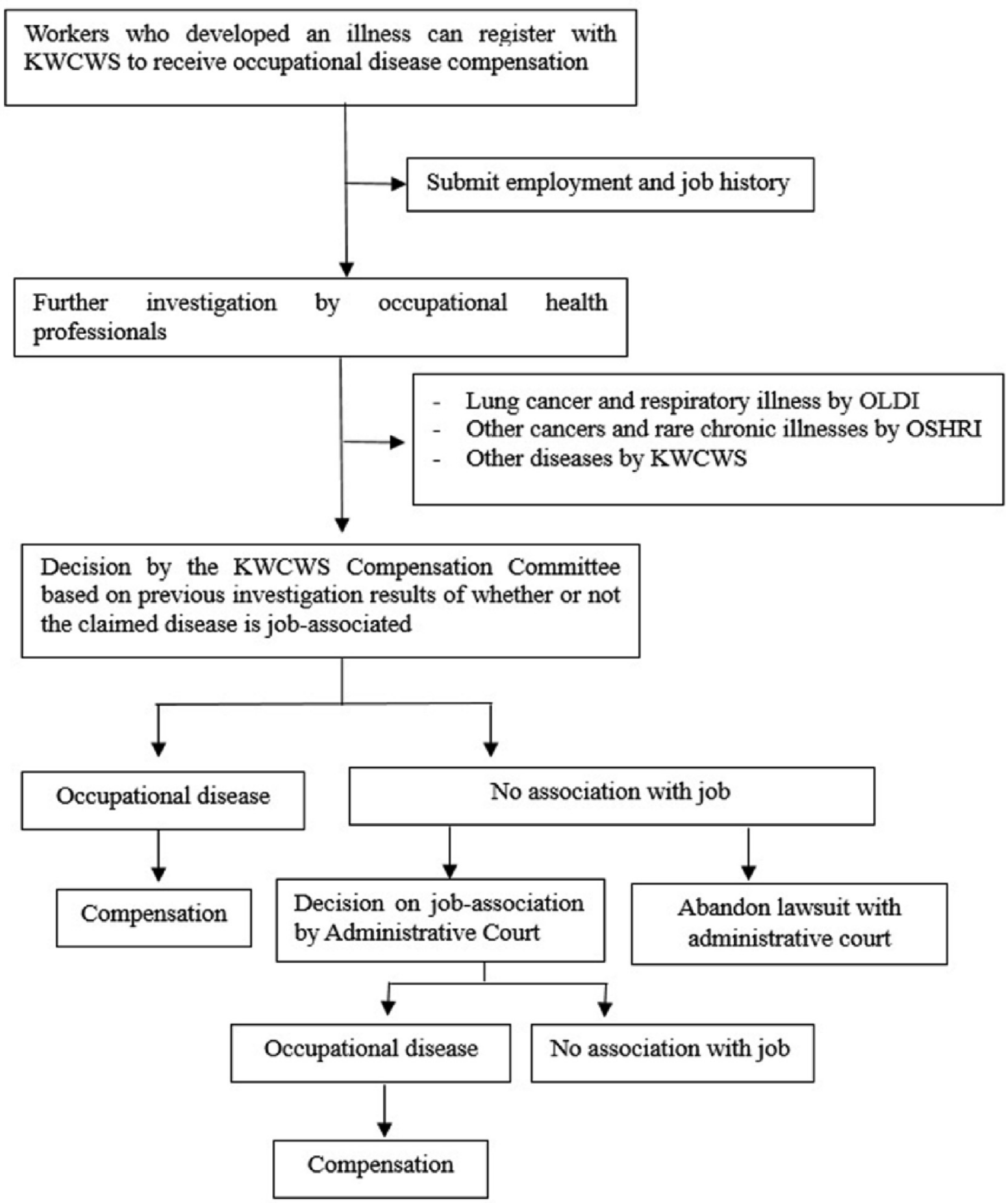

Fig. 1. Overall procedure for determining job-related disease. KWCWS, Korea Worker's Compensation and Welfare Service; OLDI, Occupational Lung Diseases Institute; OSHRI, Occupational Safety Health Research Institute.

Table 1
Operational hierarchical level and health hazards in the semiconductor industry

Major operation*	Minor operation*	Major health hazards [4–11]
Fabrication operation	Epitaxy and oxidation	Gases and silanes
	Photomasking and etching	Solvents, acids, alkalis, photoresists, developers, UV light
	Doping: diffusion and ion implantation	Gases, dopants, metals, X-ray, ELF-MF
	Deposition: chemical vapor deposition	Gases, dopants, ELF-MF
	Metallization	Dopants, metals, solvents
	Passivation	Silicon oxides and nitrides, aluminum oxide
	Testing	Chemicals in case of analysis for quality control
Chip assembly operation	Wafer backgrind/saw	Fused silica, tetramethylammonium hydroxide (TMAH)
	Die attach/wire bonding	Epoxy resins, ELF-MF
	Molding by epoxy	Epoxy resins
	Plating/marking/solder ball mounting	Chemicals from thermal decomposition of epoxy molding compound (EMC), flux
	Testing by hot and cold temperature	Chemicals from thermal decomposition of EMC, ELF-MF
Nonfabrication	Office	—
	Nonoffice operations	Supply chemical to fab clean room
		Chemicals for maintenance work outside the clean room
		Wastewater treatment and so on

* ELF-MF, extremely low-frequency magnetic field; fab, fabrication.Name and classification of the operation may vary among plants.

workers (or coworkers if claimed workers are no longer available). They submit an investigation report to the KWCWS that has first been reviewed by a committee operated by the pertinent institute. The KWCWS operates its Occupation Associated Disease Decision Committee to determine the association of a job with claimed diseases. This committee makes its decisions on the association of claimed diseases with occupations through a majority vote based on investigation results. If the association of a claimed disease with occupation is denied by the KWCWS, a worker may request the administrative court to render a judgment of occupational disease.

2.2. Study participants

Since 2007, a civil society group named Supporters for the Health and Rights of People in the Semiconductor Industry has been acting on behalf of the electronics workers in South Korea who developed chronic diseases, especially cancer and rare and incurable diseases. This organization, which included medical doctors, collected an occupational history from 82 former electronics workers, including 59 semiconductor workers, as of March 2017. Semiconductor workers with renal failure (n = 1), thyroid problems (n = 1), dermatitis (n = 1), and infertility (n = 1) who performed wafer testing for 15 years were excluded from this study because of the common nature of these diseases. The aforementioned female worker who developed infertility (n = 1) was evaluated by the KWCWS as deserving of compensation. Finally, a total of 55 semiconductor workers who had worked in wafer fab and chip (integrated circuit or microprocessor) assembly packaging operations and who had developed either cancer or a rare disease were selected for this study. A rare disease is a health condition that affects a small number of people compared with other prevalent diseases in the general population. Currently, between 5000 and 8000 rare diseases have been documented [1].

This study protocol was approved by the Institutional Review Board of Korea National Open University (IRB no. ABN01-201708-06-V1).

2.3. Brief description of semiconductor operations

The semiconductor industry was first introduced in Korea during the 1970s [2]. In South Korea, the manufacturing of semiconductors (Standard Industry Classification: SIC 261) includes the fab of integrated circuits on silicon wafers to manufacture finished chips (microprocessors) for use in electronic products (SIC 2611). The semiconductor operations in which the registered workers were involved are briefly described in the following section. The substrates for wafer and chip manufacture are grown as solid ingots in deposition chambers and then sliced into thin wafers and polished. No registered workers from those operations have been reported to date. Integrated circuits are then fabricated onto the wafer substrate through a succession of repetitive processes composed of four main operation groups: (1) patterning—oxidation, photolithography, developing, etching, and stripping; (2) junction formation—diffusion and ion implantation; (3) deposition—epitaxial or chemical vapor deposition, which is performed to deposit a thin film; and (4) metallization—sputtering and evaporation [33]. Wafers are subjected multiple times to these steps in the fab operation as they alternately add and then selectively remove materials in layers from the surface of the wafer to create the different parts of the completed integrated circuit. When the individual integrated circuits on a wafer have been completed, fabricated wafers leave the clean room of the fab operation for the chip assembly operation. There, the chips on each wafer are diced from the wafers, tested, and packaged either individually or into modules for electronic products [3–6]. The principles of semiconductor operations and the major health hazards generated in such operations have been comprehensively described elsewhere [7,8]. Major hazards are summarized by the type of the semiconductor operation and job (Table 1).

2.4. Data analysis

Registered semiconductor workers were categorized based on their work characteristics and the type of cancer or rare disease. Leukemia, non-Hodgkin lymphoma (NHL), and aplastic anemia were grouped into malignant lymphohematopoietic (LHP) disorder. Rare diseases included systemic lupus erythematosus, Wegener granulomatosis, multiple sclerosis, amyotrophic lateral sclerosis, polyneuropathy, and systemic sclerosis. Work characteristics include employment duration, the year first employed, type of operation, type of job, and wafer size handled. Registered fab workers who handled several wafer sizes over the course of their employment were coded according to the smallest size handled. Wafer size first manufactured by year is summarized based on both the literatures issued by the Samsung Economic Research Institute and statements provided by the registered fab workers (Table 2). The wafer sizes handled for chip assembly workers were coded as "not applicable" because of little association with hazards. Descriptive data analysis was used to compare the distribution of semiconductor workers based on the types of work characteristics

Table 2
Wafer size first manufactured by year at company "A."

Year	Wafer size first manufactured, inches (mm)*
1984	4 (50)
1985	6 (150)
1988	6
1989	6
1992	8 (200)
1994	8
1995	8
1996	8
1999	8
2000	8
2001	8 and 12 (300)
2003	12

* Indicating only the year that a specific wafer size was first manufactured. For example, the oldest production line manufactured 4-inch wafers until the end of 2004. In 2003, most production lines still manufactured ≤ 8-inch wafers.

or types of diseases. All statistical analyses were performed using STATA version 12 (StataCorp, College Station, Texas, USA).

3. Results

We found that registered semiconductor workers had been diagnosed with nine types of cancer (leukemia = 14, breast = 10, brain = 6, NHL = 4, lung = 3, thyroid = 3, malignant lymphoma = 2, ovarian = 1, and osteosarcoma = 1) (Table 3). LHP disorder accounted for 44% (n = 24) of cases among registered workers. The number of workers involved in fab clean room operations was 34 (62%), considerably higher than the 19 employed in chip assembly operations, who all worked in a clean room. Only two workers worked outside a clean room. They were involved in wastewater treatment and chemical supply to fab operations. Type of major operation (fab), year first employed being before 2000, and etching operation were common work characteristics identified among registered workers, which indicated an association with chronic diseases including cancer incidence risk. In particular, 60% (n = 33) of registered workers were found to have been employed before 2000 (Fig. 2). Furthermore, 76% (n = 42) of registered workers were found to be diagnosed at a relatively young age (≤40 years). Among four aplastic anemia cases reported, one is accompanied by paroxysmal nocturnal hemoglobinuria. Leukemia cases consisted of the following subtypes: acute myelogenous leukemia (n = 9), acute lymphoblastic leukemia (n = 4), and chronic myelogenous leukemia (n = 1). All lymphoma cases are NHL (n = 6). Nineteen among the registered workers with LHP (n = 24) developed their diseases at ≤40 years. Two registered workers with lung cancer who were involved in the etching process were both compensated for occupational disease.

A total of 18 workers among the registered semiconductor workers were finally determined to deserve compensation for occupational disease by either the KWCWS (n = 10) or the administrative court (n = 8) (Table 4). The administrative court awarded compensation based on the comprehensive association of the claimed diseases with occupational characteristics, even if the status of occupational disease had been denied by the KWCWS. The number of workers compensated by major operation was 12 for fab and five for chip assembly. Eleven fab workers responded as having handled wafers eight inches or less in size. Eight among the 18 workers compensated (44 %) were found to have ever worked at etching operations. Workers with LHP (leukemia = 4, aplastic anemia = 3, and malignant lymphoma = 1) accounted for 44% among compensated semiconductor workers.

4. Discussion

The most common cancer registered was leukemia (n = 14), followed by breast cancer (n = 10) and brain cancer (n = 6). Forty-four percent (n = 24) of the registered workers were found to have developed LHP disorders (Tables 3 and 4). We identified possible common occupational characteristics related to the distribution of the registered claimed diseases. These are the year first employed, wafer size handled, exposure to clean room, and etching within fab operation, although this trend does not prove a causal relationship between claimed diseases and work characteristics.

Eighty-seven percent (n = 48) of the workers registered (n = 55) and all compensated workers (n = 18) were found to have started work before 2005, when smaller wafers of a size of ≤ 8 inches were likely manufactured. The majority of workers who claimed leukemia (12 among the 14 registered workers), breast cancer (eight among the 10 registered workers), NHL (five among the six registered workers), and brain cancer (all) were hired before 2005 (Table 3, Fig. 2). The year first employed is likely related to the wafer manufacturing era before 2005. All registered workers who worked before 2005 responded as having handled wafers ≤ 8 inches, indicating that chemicals and products were handled manually, although there have been no published articles reporting on the changes in the semiconductor work environment, such as in regard to operation, level of automation, or frequency of manual handling. According to a report by the Samsung Economic Research Institute, the manufacture of 12-inch wafers was first tested around the end of the 1990s through a pilot process. Around 2002, large-scale manufacturing of DRAM from 12-inch wafers began. Based on a statement made by registered workers and data reported by the Samsung Economic Research Institute (Table 2), fab workers employed before 2005 can be assumed to have handled wafers <12 inches in size, indicating that most of the semiconductor processes were manually performed. The smallest wafer size, 4 inches, was found to be manufactured until the end of 2004 in the oldest production line. When wafers were <12 inches, the frequency of manual loading and unloading of chemicals and products was likely to be frequent, resulting in higher exposure among workers. Most of the registered workers responded that they handled chemicals and products manually, but there has been no study to assess their exposure to chemicals. All production lines and operations in which the registered workers were involved were either eliminated or replaced upon the introduction of new manufacturing processes for larger wafers. As wafers grew in size, automation became more widespread because the wafers increased in weight and became too heavy for human operators. During this period, the frequency with which operators physically handled wafers and chemicals decreased as chemical supply systems and wafer loading and unloading became almost entirely automated [13]. Only 12-inch wafers are currently fabricated by the two large companies in Korea ("A" and "B," Tables 2 and 3). Only 12-inch wafers were being manufactured by around early 2012 at company "A" and 2009 at company "B." According to the literature reported in the US, the 1-inch diameter wafer of the 1960s gave way to the 200-mm (8-inch) size around the mid-1990s and to the 300-mm (12-inch) size since the mid-1990s [4]. This is far earlier than the eras when wafers of these sizes were manufactured in Korea (Table 2).

Most registered workers (n = 53) were found to have worked inside clean rooms in fab and chip assembly operations. In particular, 34 (62%) of the registered workers and 14 (58%) of the workers with LHP were found to have worked in a fab clean room operation (Table 3). The cleanliness of the room is highly controlled to limit the amount of dust to which the semiconductor is exposed [4]. The concept of cleanliness, however, is not connected to the promotion of human health. Seven (50%) among the 18 workers compensated

Table 3
Distribution of registered workers (n = 55) by the type of disease and type of work characteristics

Demographic and occupational classification	Leukemia	NHL	Other lymphohematopoietic disorder[*]	Subtotal[†]	Breast	Brain	Lung	Other cancers[‡]	Rare diseases[§]	Total
Sex										
Male	8	2	2	12	0	1	3	2	3	21
Female	6	2	4	12	10	5	0	3	4	34
Age										
<29	5	2	3	10	0	1	0	1	3	15
30–34	2	0	1	3	4	3	0	1	0	11
35–39	3	1	2	6	1	1	2	2	3	15
40–44	1	0	0	1	3	1	1	1	0	7
45–49	2	0	0	2	0	0	0	0	1	3
50–54	1	1	0	2	1	0	0	0	0	3
55–59	0	0	0	0	1	0	0	0	0	1
Type of operation										
Fab	10	1	3	14	6	2	3	3	6	34
Chip	4	2	3	9	4	4	0	2	0	19
Outside clean room	0	1	0	1	0	0	0	0	1	2
Type of job										
Operator	7	2	4	13	10	5	0	3	4	35
Maintenance	6	2	2	10	0	1	3	2	3	19
Product quality analysis	1	0	0	1	0	0	0	0	0	1
Year first employed										
<2000	8	1	2	11	7	3	2	5	5	33
2000–2005	4	2	3	9	1	3	1	0	1	15
2006–2010	1	0	1	2	2	0	0	0	0	4
2011–2015	1	1	0	2	0	0	0	0	1	3
Duration employed, year										
<=5	5	2	4	11	7	3	0	1	5	27
6–10	4	1	2	7	2	2	0	3	0	14
11–15	2	1	0	3	0	0	1	0	2	6
16–20	0	0	0	0	0	1	2	0	0	3
>20	3	0	0	3	1	0	0	1	0	5
Wafer size handled, inch[‖]										
4	2	0	0	2	0	2	1	0	1	6
6	5	0	1	6	2	0	0	2	1	11
8	1	1	1	3	4	0	2	1	4	14
12	2	0	1	3	0	0	0	0	0	3
NA	4	3	3	10	4	4	0	2	1	21
Operation[¶]										
Fab operation clean room										
Etching	1	1	1	3	1	1	2	0	0	7
Photo	0	0	1	1	1	0	1	2	2	7
Implantation	1	0	0	1	0	1	0	0	0	2
Diffusion	2	0	0	2	1	0	0	0	2	5
CVD	0	0	0	0	0	0	0	1	1	2
Maintenance for auto transportation facility	1	0	0	1	0	0	0	0	0	1
Several operations	0	0	1	1	0	0	0	0	0	1
Several operations including etching	2	0	0	2	2	0	0	0	1	5
CMP	1	0	0	1	0	0	0	0	0	1
Test	0	0	0	0	1	0	0	0	0	1
Supervisor	1	0	0	1	0	0	0	0	0	1
Chemical analysis	1	0	0	1	0	0	0	0	0	1
Outside fab operation										
CCSS	0	1	0	1	0	0	0	0	0	1
Wastewater treatment in fab operation	0	0	0	0	0	0	0	0	1	1
Chip assembly										
MVP	0	0	0	0	0	2	0	0	0	2
Test	1	1	2	4	2	2	0	0	0	8
Plating/cutting/bending	1	1	1	3	0	0	0	0	0	3
Molding	0	0	0	0	1	0	0	1	0	2
Oven/mixing	1	0	0	1	0	0	0	0	0	1
Bonding	1	0	0	1	0	0	0	1	0	2
Cleaning	0	0	0	0	1	0	0	0	0	1
Total	14	4	6	24	10	6	3	5	7	55

CVD, chemical vapor deposition; fab, fabrication; NHL, non-Hodgkin lymphoma; SLE, systemic lupus erythematosus; CMP, chemical mechanical polishing; CCSS, chemical control supply system; MVP, marking visual packing.

[*] Includes aplastic anemia (n = 4) and malignant lymphoma (n = 2).

[†] Malignant lymphohematopoietic (LHP) disorder.

[‡] Includes osteosarcoma (n = 1), thyroid (n = 3), and ovarian (n = 1).

[§] Includes SLE (n = 2), amyotrophic lateral sclerosis (n = 1), multiple sclerosis (n = 1), polyneuropathy (n = 1), systemic sclerosis (n = 1), and Wegener granulomatosis (n = 1).

[‖] Four- and 6-inch wafers handled are coded as 4 inches (n = 3); 4- and 8-inch wafers, as 4 inches (n = 2); 4-, 6-, and 8-inch wafers, as 4 inches (n = 2); 6- and 8-inch wafers, as 6 inches (n = 4); and 8- and 12-inch wafers, as 8 inches (n = 1).

[¶] Working duration longer than 50% of employment.

(31%) and 12 (22%) among all the registered workers were found to have been involved in etching operations. Two workers compensated for lung cancer and five workers compensated for LHP disorders (leukemia = 3, aplastic anemia = 1, and NHL = 1) were found to have performed etching operations. Four etching workers compensated were found to have started work before the year 2000 (before 1990 = 2, 1994 = 1, and 1999 = 1). Etching is used to remove deposited films or substrates where they are not protected

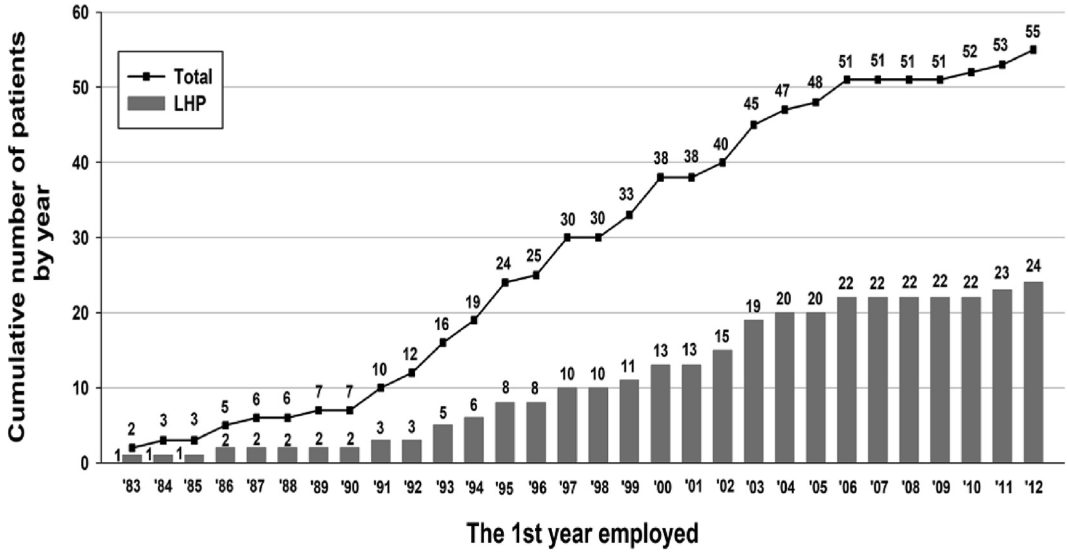

Fig. 2. Cumulative distribution of diseases developed by registered semiconductor workers (n = 55) by the year first employed (LHP = malignant lymphohematopoietic disorder, including leukemia, NHL, and aplastic anemia; n = 24). LHP, lymphohematopoietic; NHL, non-Hodgkin lymphoma.

by the photoresist and consists of wet etching and dry etching. Wet etching refers to the removal of materials (usually in specific patterns defined by photoresist masks on the wafer) from the wafer by using liquid chemicals or etchants such as hydrofluoric acid, hydrochloric acid, sulfuric acid, nitric acid, chromium trioxide, and hydrogen peroxide [11].

Dry etching refers to the removal of materials by exposing the material to a bombardment of ions (usually plasma of reactive gases such as fluorocarbons, oxygen, chlorine, or boron trichloride) that dislodge portions of the material from the exposed surface [14]. This operation is known to require the extensive use of strong and highly caustic chemicals. In wet etching, the wafers were manually dipped in baths containing acids (e.g., nitric acetic and

Table 4
Occupational history of semiconductor workers compensated (n = 18) as of July 2017

Sex	Age†	Disease compensated	Company‡	Major operation	Minor operation	Job title	First year employed	Wafer size handled, inches	Employment duration, years	Work-related compensated organization
Female*	21	Leukemia	A	Fab	Diffusion Etching	Operator Operator	2003 2004	6 6	1.1 0.6	Administrative court
Female*	31	Leukemia	A	Fab	Deposition CVD Marking Etching Diffusion Etching	Operator Operator Operator Operator Operator Operator	1995 2001 2004 2005 2005 2006	6 6 6 6 6 6	12 3 0.8 0.4 0.6 0.2	Administrative court
Female	20	Aplastic anemia	A	Chip	Test	Operator	2000	NA	1.3	Administrative court
Female*	29	Leukemia	A	Fab	Etching	Operator	1999	6	4.8	Administrative court
Male	43	Brain	A	Fab	Implantation	Maintenance	1983	4, 6, and 8	18.7	KWCWS
Female*	25	Ovarian	A	Chip	Bonding	Operator	1993	NA	6.2	Administrative court
Female	35	Aplastic anemia	A	Chip	Cutting and electroplating	Operator	1993	NA	6.4	KWCWS
Female*	34	Breast	A	Fab	Implantation	Operator	1995	8	3.3	KWCWS
					Etching and photo	Operator	1998	8	1.3	
Male*	38	Leukemia	B	Fab	Implantation	Maintenance	1997	6 and 8	13.3	KWCWS
Female*	28	Malignant lymphoma	A	Fab	Photo	Operator	2002	8	3.8	KWCWS
Male*	39	Lung	A	Fab	Etching	Maintenance	1994	8 and 12	16.6	KWCWS
Male*	44	Lung	A	Fab	Etching	Maintenance	1984	4	17.3	KWCWS
Female*	41	Breast	C	Chip	Sawing, mounting, test	Operator	1987	NA	28	KWCWS
Male	36	Malignant lymphoma	B	Fab	Implantation/CVD	Maintenance	1995	6 and 8	9.8	KWCWS
Male	45	Polyneuropathy	C	Outside fab	Wastewater treatment	Maintenance	2012	NA	0.8	Administrative court
Female	25	Multiple sclerosis	A	Fab	CVD/etching Photo	Operator Operator	2003 2004	8 8	1.2 0.8	Administrative court
Male*	32	Aplastic anemia	A	Fab	Etching	Maintenance	2003	12	5.4	KWCWS
Female*	31	Brain	A	Chip	Test	Operator	1997	NA	6.2	Administrative court

* CVD, chemical vapor deposition; fab, fabrication; KWCWS, Korea Worker's Compensation and Welfare Service; NA, not applicable.Death.
† Age when diagnosed.
‡ The same letters indicate the same company.

hydrofluoric acid). Workers would be likely exposed to high levels of these acids when pouring acid, dipping wafers, and disposing of acid manually. To our knowledge, no study has reported on the inhalation exposure levels to the chemicals used in this process [15]. Specific operations within the fab may be related to a risk of cancer, although a specific type of cancer cannot be defined.

Breast cancer (n = 10), brain cancer (n = 6), NHL (n = 4), thyroid (n = 3), lung cancer (n = 3), and ovarian cancer (n = 1) registered with the KWCWS have been already reported to be associated with semiconductor operations in cancer risk epidemiologic studies. A total of eight epidemiologic studies conducted in the UK and USA semiconductor industries evaluated ten types of cancer to be significantly associated: melanoma, rectum, prostate, pancreas, breast (no. of studies = 2), brain, ovarian, lung, thyroid, and stomach (n = 1) [16–23]. In South Korea, the incidence of NHL among female operators in chip assembly manufacturing operation was evaluated to be significant (Standardized incidence rate (SIR) = 3.15, 95% confidence interval = 1.02–7.36, 5 cases) [24]. None of the epidemiologic cancer risk studies to date has reported a significantly increased risk of leukemia, the disease most commonly claimed in this study. Leukemia and NHL are rare cancers in South Korea. Age-adjusted incidence rates for leukemia and NHL in 2009 were 4.8 and 6.3 per 100,000 people, respectively [25,26]. Hematopoietic cancer among semiconductor workers has been the subject of major public concern in Korea [27]. Acquired aplastic anemia is a syndrome characterized by hypocellular bone marrow, nonincrease in blast cell number or fibrosis, and peripheral pancytopenia [28]. The cause of aplastic anemia is generally unknown, but exposure to ionizing radiation, benzene, inorganic arsenic, certain drugs (e.g., alkylating agents), and certain infections (e.g., viral hepatitis) is known or considered to be associated with development of aplastic anemia [28–30]. Benzene-induced aplastic anemia case reports appear in many literatures, especially when benzene toxicity was not largely recognized [31]. Benzene-induced aplastic anemia commonly evolved to leukemia, mostly acute myelogenous leukemia, although acute lymphoblastic leukemia, chronic lymphoblastic leukemia, and chronic myelogenous leukemia cases are also reported [31]. Lymphomas, including Hodgkin lymphoma and NHL cases, were also reported in workers heavily exposed to benzene in the early literature [5]. The incidence of acquired aplastic anemia is about 2/million in Western countries, but in Asian countries, the incidence is reported to be 2–3 times greater than that of the Western countries [3]. In our study, we could not calculate exact incidence of aplastic anemia, but we suspect four cases may suggest a higher risk of aplastic anemia. The causative agent of the semiconductor industry probably includes benzene, but ionizing radiation, arsenic, cellosolve, and extremely low-frequency magnetic field (ELF-MF) also should be considered in the future study.

Several cases of rare disease (systemic lupus erythematosus = 2, osteosarcoma = 1, amyotrophic lateral sclerosis = 1, Wegener granulomatosis = 1, systemic sclerosis = 1, multiple sclerosis = 1, and polyneuropathy = 1) were registered. Only two semiconductor workers with polyneuropathy and multiple sclerosis to date were compensated by the administrative court (Table 4) because KWCWS's Compensation Committee has applied the criterion that registered workers should be exposed to disease-causing agents confirmed by the International Agency for Research on Cancer or in the existing literature. The KWCWS requires registered workers to prove exposure to causative agents either quantitatively or qualitatively, which can present an insurmountable obstacle. It is nearly impossible for workers who develop rare diseases infrequently reported in workplaces to receive compensation as an occupational disease. Workers who fail to provide occupational history information to prove their claimed disease are likely to get occupational disease compensation from the KWCWS [32]. It is extremely rare for workers to have access to the occupational characteristics with which they were involved. In addition, an investigation team responsible for estimating past exposure is unable to find information for operations and production lines in the past when there is a lack of employer cooperation or no well-recorded work history.

The job histories investigated showed no known consistent and specific operations or suspected agents closely associated with a risk of the claimed cancers, including LHP. There is a need for evaluation of new and emerging risks, including cancer, in semiconductor operations, although no clear-cut link to the work environment or tasks performed has been established. It has been well reported that semiconductor workers are generally exposed to ELF-MFs [33,34] and to low levels of many chemicals [18]. Choi et al. [35] reported average levels of ELF-MF exposure of 0.56 μT (no. of workers = 58, range: 0.01–35.36 μT) for fab workers and 0.59 μT (n = 45, range: 0.01–26.72 μT) for chip packaging workers assessed in Korea. In addition, fab workers can be exposed to low levels of complex chemicals, including by-products that are recirculated from the various fab operations [18,36]. The wafer fab process involves the use of potentially hazardous chemicals such as metals, photoactive chemicals, organic solvents, acids, and toxic gases in a wide variety of combinations and workplace settings. Very few epidemiological data are available regarding the possible combined effects of ELF-MFs with other environmental agents, including chemicals. Navas-Acien et al. [37] addressed possible interactions between exposure to ELF-MFs and chemical substances with known or suspected carcinogenic effects in a cohort of male Swedish workers. Lead, pesticides, arsenic, and solvents have all been associated with increased glioma risk only in participants exposed to high (>0.2 uT) to moderate levels of ELF-MFs (0.13–0.20 uT). Hakansson et al. [38] conducted a case–control study of endocrine gland (adrenal gland, thyroid gland, and parathyroid gland) tumors and reported increased risks associated with welding and exposure to solvents, which was interpreted as a possible association with exposure to ELF-MFs. Semiconductor workers have been partly or fully exposed to ELF-MFs and a wide range of chemicals, which may be associated with various types of health problems, including cancer. An epidemiologic study is required to evaluate the cancer risk of possible combined effects of ELF-MFs with the many chemicals used in semiconductor operations.

This study has a limitation in estimating the incidence risk of the cancers and rare diseases registered because we were unable to identify not only the number of actual semiconductor workers who were employed in specific operations during specific periods but also the actual number of semiconductor workers with chronic diseases, including the several types of cancers and rare diseases indicated here. Semiconductor workers who have registered with a compensation program could be highly self-selective. The number of semiconductor workers who register with the KWCWS, and accordingly the number of approved cases, is likely to increase over time.

This study identified common job characteristics, including operation and job type among semiconductor workers who registered with the KWCWS, that may be associated with risk of chronic diseases. Our results contribute to further epidemiologic study not only because they classify semiconductor workers based on exposure profile but also because they evaluate cancer risk among semiconductor workers. In addition, there is little or no actual exposure information in most cases, especially before 2005. The quality of workers' occupational profiles recorded by the company, access to company records related to past manufacturing lines and operations, and the narratives of the victims vary among companies and registered workers, which affects the quality of occupational information assessed in this study. It is very difficult to study because of the latency of these kinds of chronic diseases, high turnover worker populations, rapidly evolving production process and materials, and secrecy of the semiconductor industry. Nonetheless, this study identified common job characteristics, including operation and job type among semiconductor workers who registered with the KWCWS, that may be associated with risk of chronic diseases.

In conclusion, the distribution of cancer and rare diseases among semiconductor workers who registered with the KWCWS was closely related to the manufacturing era before 2005, $\leq$8 inches of wafer size handled, exposure to clean rooms of fab and chip assembly operations, and etching operations. LHP disorders, including leukemia, NHL, and aplastic anemia, and breast cancer were found to be the most frequent complaints.

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Conflicts of interest

All authors have no conflicts of interest to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2019.03.003.

References

[1] Richter T, Nestler-Parr S, Babela R, Khan ZM, Tesoro T, Molsen E, Hughes DA. Rare disease terminology and definitions—a systematic global review: report of the ISPOR rare disease special interest group. Value Health 2015;18:906–14.
[2] Park JY. History of development in Korea semiconductor industry. Korea Semiconductor Industry Association; 2012.
[3] Marano DE, Boice Jr JD, Munro HM, Chadda BK, Williams ME, McCarthy CM, Kivel PF, Blot WJ, McLaughlin JK. Exposure assessment among US workers employed in semiconductor wafer fabrication. J Occup Environ Med 2010;52:1075–81.
[4] Van Zant P. Microchip fabrication: a practical guide to semiconductor processing. New York: McGrawHill; 2004. p. 63–4.
[5] Wald PH, Jones JR. Semiconductor manufacturing: an introduction to processes and hazards. Am J Ind Med 1987;11:203–21.
[6] Harrison M. Semiconductor manufacturing hazards. In: Hazardous materials toxicology: clinical principles of environmental health. Williams & Wilkins; 1992. p. 472–504.
[7] Chelton C, Glowatz M, Mosovsky J. Chemical hazards in the semiconductor industry. IEEE Trans Educ 1991;34:269–88.
[8] Singapore Ministry of Manpower. A Guide on health hazards and their control in wafer fabrication facilities. Occupational Safety and Health Division; 1998.
[9] Baldwin D, King B, Scarpace L. Ion Implanters-Chemical and radiation safety. Solid State Technol 1988;31:99–105.
[10] Van Zant P, Chapman P. Microchip fabrication: a practical guide to semiconductor processing. New York: McGraw-Hill; 2000.
[11] Hawkinson TE. Chemical hazards in semiconductor operations. Semiconductor safety handbook: safety and health in the semiconductor industry. New York: William Andrew Publishing/Noyes; 1998. p. 163–79.
[13] Research and Development Foundation of Seoul National University. Risk assessment in semiconductor industry: Part 1. Exposure assessment. Research Report; 2009.
[14] Yao D, Pardon A, Van Hoornick N, Lievens P. Process risk assessment of semiconductor wet chemical cleaning techniques. Group T Engineering College; 2007.
[15] Byun K, Won YL, Hwang YI, Koh DH, Im H, Kim EA. Assessment of arsenic exposure by measurement of urinary speciated inorganic arsenic metabolites in workers in a semiconductor manufacturing plant. Ann Occup Environ Med 2013;25:21.
[16] Beall C, Bender TJ, Cheng H, Herrick R, Kahn A, Matthews R, Sathiakumar N, Schymura M, Stewart J, Delzell E. Mortality among semiconductor and storage device-manufacturing workers. J Occup Environ Med 2005;47:996–1014.
[17] Bender TJ, Beall C, Cheng H, Herrick RF, Kahn AR, Matthews R, Sathiakumar N, Schymura M, Stewart J, Delzell E. Cancer incidence among semiconductor and electronic storage device workers. Occup Environ Med 2007;64:30–6.
[18] Boice Jr JD, Marano DE, Munro HM, Chadda BK, Signorello LB, Tarone RE, Blot WJ, McLaughlin JK. Cancer mortality among US workers employed in semiconductor wafer fabrication. J Occup Environ Med 2010;52:1082–97.
[19] Darnton A, Wilkinson S, Miler B, MacCalman L, Galea K, Shafrir A, Cherrie J, McElvenny D, Osman J. A further study of cancer among the current and former employees of National Semiconductor (UK) Ltd. Greenock. Sudbury, Suffolk (UK): Health and Safety Executive and Institute of Occupational Medicine; 2010. 135 p.
[20] McElvenny DM, Darnton AJ, Hodgson JT, Clarke SD, Elliott RC, Osman J. Investigation of cancer incidence and mortality at a Scottish semiconductor manufacturing facility. Occup Med 2003;53:419–30.
[21] Nichols L, Sorahan T. Cancer incidence and cancer mortality in a cohort of UK semiconductor workers, 1970-2002. Occup Med 2005;55:625–30.
[22] Sorahan T, Pope D, McKiernan M. Cancer incidence and cancer mortality in a cohort of semiconductor workers: an update. Br J Ind Med 1992;49:215. PMCID: PMC1012097.
[23] Sorahan T, Waterhouse J, McKiernan M, Aston R. Cancer incidence and cancer mortality in a cohort of semiconductor workers. Occup Environ Med 1985;42:546–50.
[24] Lee HE, Kim EA, Park JS, Kang SK. Cancer mortality and incidence in Korean semiconductor workers. Saf Health Work 2011;2:135–47.
[25] Statistics Korea. The statistics for cause of death in 2009; 2009. Available from: http://kostat.go.kr/.
[26] Ministry of Health and Welfare. National cancer registration and statistics system. In: Annual report of cancer statistics in Korea in 2009 2011. Available from: https://ncrs.cancer.go.kr/; 2011.
[27] Kim EA, Lee HE, Ryu HW, Park SH, Kang SK. Cases series of malignant lymphohematopoietic disorder in Korean semiconductor industry. Saf Health Work 2011;2:122–34.
[28] Issaragrisil S, Kaufman DW, Anderson T, Chansung K, Leaverton PE, Shapiro S, Neal SY. The epidemiology of aplastic anemia in Thailand. Blood 2006;107:1299–307.
[29] Muir K, Chilvers C, Harriss C, Coulson L, Grainge M, Darbyshire P, Hows CGJ, Marsh J, Rutherford T, Taylor M, Gordon-Smith EC. The role of occupational and environmental exposures in the aetiology of acquired severe aplastic anaemia: a case control investigation. Brit J Haematol 2003;123:906–14.
[30] Young NS, Kaufman DW. The epidemiology of acquired aplastic anemia. Haematologica 2008;93:489–92.
[31] Goldstein BD. Benzene toxicity: a critical evaluation: hematotoxicity in humans. J Tox Environ Health Suppl 1977;2:69–105. PMID:342717.
[32] Korea Ministry of Employment and Labor. Industrial accident compensation insurance act; 2017. Available from: http://www.law.go.kr/.
[33] Chung EK, Kim KB, Chung KJ, Lee IS, You KH, Park JS. Occupational exposure of semiconductor workers to ELF magnetic fields. J Korean Soc Occup Environ Hyg 2012;22:42–51.
[34] Abdollahzadeh S, Katharine SH, Schenker MB. A model for assessing occupational exposure to extremely low-frequency magnetic fields in fabrication rooms in the semiconductor health study. Am J Ind Med 1995;28:723–34.
[35] Choi S, Cha W, Park J, Kim S, Kim W, Yoon S, Park JH, Ha K, Park D. Extremely low frequency-magnetic fields (ELF-MF) exposure characteristics among semiconductor workers. Int J Environ Res Public Health 2018;15:642.
[36] Park HH, Jang JK, Shin JA. Quantitative exposure assessment of various chemical substances in a wafer fabrication industry facility. Saf Health Work 2011;2:39–51.
[37] Navas-Acién A, Pollán M, Gustavsson P, Floderus B, Plato N, Dosemeci M. Interactive effect of chemical substances and occupational electromagnetic field exposure on the risk of gliomas and meningiomas in Swedish men. Cancer Epidemiol Biomarkers Prev 2002;11:1678–83.
[38] Håkansson N, Stenlund C, Gustavsson P, Johansen C, Floderus B. Arc and resistance welding and tumours of the endocrine glands: a Swedish case-control study with focus on extremely low frequency magnetic fields. Occup Environ Med 2005;62:304–8.