Assessment of working environment and personal dosimeter-wearing compliance of industrial radiographers based on chromosome aberration frequencies

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Abstract

Industrial radiographers are exposed to relatively higher doses of radiation than other radiation-exposed workers in South Korea. The objective of our study was to investigate the impact of specific occupational conditions on chromosome aberration frequency and evaluate dosimeter-wearing compliance of industrial radiographers in Korea. We studied individual and occupational characteristics of 120 industrial radiographers working in South Korea and evaluated the frequency of dicentrics and translocations in chromosomes to estimate radiation exposure. The association between working conditions and chromosome aberration frequencies was assessed by Poisson regression analysis after adjusting for confounding factors. Legal personal dosimeter-wearing compliance among workers was investigated by correlation analysis between recorded dose and chromosome aberration frequency. Daily average number of radiographic films used in the last six months was associated with dicentrics frequency. Workers performing site radiography showed...
significantly higher translocation frequency than those working predominantly in shielded enclosures. The correlation between chromosome aberration frequency and recorded dose was higher in workers in the radiography occupation since 2012 (new workers) than other veteran workers. Our study found that site radiography could affect actual radiation exposure to workers. Controlling these working conditions and making an effort to improve personal dosimeter-wearing compliance among veteran workers as well as new workers may be necessary to reduce radiation exposure as much as possible in their workplace.

Keywords: industrial radiographers, chromosome aberrations, occupational environments, personal dosimeter-wearing compliance

Introduction

Industrial radiography is a nondestructive testing method used to verify the integrity and structure of materials [1, 2]. This method inspects vessels, pipes, welded joints, and other devices to identify hidden flaws or cracks with the help of x-rays or γ-emitting sources. Industrial radiography requires confined spaces and extreme temperatures, posing an operational challenge in achieving reasonably low radiation exposure dose. The number of industrial radiographers in South Korea has consistently increased, from 5323 in 2008 to 7645 in 2015 [3, 4]. The annual average effective dose that these workers are exposed to in the last five years is 1.77–3.87 mSv, higher than that in workers in other radiation-related occupations [4]. Although radiation exposure of workers has been managed below the legal dose limit, 100 mSv in five years or 50 mSv in any single year, repeated radiation overexposure cases in nondestructive testing have been reported [5]. Cases diagnosed with acute radiation syndrome, azoospermia, and hematological malignancies were reported and their radiation overexposure was confirmed by comprehensive evaluation including personal dose assessment and working history [5–7]. Since the occurrence of three deaths due to hematological malignancies in the same nondestructive testing company in 2011–2012, the Nuclear Safety and Security Commission (NSSC) in South Korea has strengthened related legislation and support for radiographers’ safety—for example, reporting daily time to perform radiography and providing financial support for the installation of dose monitoring devices and warning lights.

Interviews with the victims revealed several issues in the working environment and practices, such as using a maximum of 400 sheets of radiographic films per day, working in high places of the large pipe surface without any shielding, and working without a personal dosimeter [5, 6]. These poor conditions are directly related to occupational exposure and health effects. The actual exposure of individual workers can be different depending on their work habits, availability of radiation safety equipment, infrastructural facilities to protect against radiation exposure, and individual knowledge of the potential health hazards of occupational radiation exposure. Therefore, it is necessary to evaluate workers’ actual radiation exposure and investigate the association between working environment and actual exposure.

A representative method to monitor individual radiation exposure is the use of personal dosimeters such as a thermoluminescent dosimeter (TLD) and/or film badges [2]. These
dosimeters help monitor occupationally exposed dose of radiation and control radiation exposure below the legal dose limit. However, discrepancies between physically recorded doses by personal dosimeters and biologically estimated doses indicated that radiation-exposed workers did not wear personal dosimeters during work [5–7, 8]. Although all radiographers should wear personal dosimeters during work [2], it was revealed that some workers often did not carry a legal dosimeter in the workplace [6]. Lack of awareness of the importance of dose monitoring or improper handling of personal dosimeters can result in a poor dosimeter-wearing practice and possibly cause incorrect estimation of radiation dose. Errors in exposure measurement may lead to biased estimates of radiation-induced health risk in epidemiological studies.

Biological dosimetry is the assessment of the absorbed dose of ionising radiation by measuring radiation-induced biological and biophysical changes to estimate the dose from exposure to ionising radiation [9–11]. Chromosome aberrations in peripheral blood lymphocytes have been widely accepted for many years as biological markers of exposure to ionising radiation [12–16]. The well-established markers of chromosome aberrations are dicentrics and translocation, which have been used for estimating the dose received by radiation workers or victims of radiation accidents as a complementary tool to physical dosimetry [8, 12, 14, 16–18]. In addition, it could help evaluate personal dosimeter-wearing compliance of workers by comparing with personal dosimeter results. A dicentric chromosome is an aberrant chromosome bearing two centromeres derived from the misrepair of two broken chromosomes [19]. A dicentric chromosome assay is the gold standard method for radiation biodosimetry. As it disappears with time after radiation exposure due to the limited lifespan of lymphocytes, it is typically used as a marker to identify recent acute radiation exposure [14, 20]. Translocation is a chromosome alteration in which a whole chromosome or segment of a chromosome becomes attached to or interchanged with another whole chromosome or segment, the resulting hybrid segregating together at meiosis [19]. Stable cells containing translocation can survive through the cell cycle, thereby serving as a tool for dose assessment even years after radiation exposure [14, 20–23]. Translocation frequency can be affected by individual and environmental factors such as age, smoking, alcohol, and other pollutants, and their confounding effects need to be considered [14, 24].

To explore hazardous occupational conditions or non-compliant behavior of industrial radiographers in Korea, we investigated the impact of occupational conditions on actual radiation exposure of industrial radiographers and evaluated their dosimeter-wearing habit. We obtained individual and occupational characteristics of radiographers using the industrial radiography-related survey questionnaire, which Seo et al. (2018) developed to collect detailed information on the work status of industrial radiographers [25]. The frequency of chromosome aberrations such as dicentrics and translocations was evaluated to assess actual radiation exposure of radiographers. In the present study, we showed the impact of recent workloads and the main inspections of workplaces of Korean industrial radiographers on chromosome aberration frequency and their personal dosimeter-wearing habits by investigating the association between workers’ individual and occupational factors and chromosome aberration frequency.

Materials and methods

Study population and design

This study has been approved by the Institutional Review Board of the Korea Institute of Radiological and Medical Sciences (IRB No. KIRAMS 2018-03-005-004). Written informed
consent for participating in this study was obtained from each individual. The study population was composed of 120 male industrial radiographers. All subjects completed a self-administered questionnaire composed of questions about general work history, lifestyle factors, demographics, and additional radiography-related questions [25].

**Personal dosimeter records**

Occupational radiation exposure of industrial radiographers was monitored with a legal personal dosimeter. Their official personal dosimetry records were procured from the Central Registry for Radiation Worker Information (CRRWI) managed by the NSSC. When their recorded dose was below 0.1 mSv, ‘below recording dose’ was registered in the CRRWI. Last annual dose and lifetime dose was calculated based on individual monthly records. To consider the lifetime of lymphocytes when comparing the recorded dose with the chromosome aberration yields at the time of blood collection, the concept of ‘equivalent acute dose’ has been introduced [26, 27]. Equivalent acute dose was calculated by weighting annual recorded doses of chronically exposed radiation workers for the half-life of lymphocytes of three years (the mean lifetime of 4.3 years) by using the formula: ΣAnnual dose × exp(−(0.693 × t/T_1/2)), where t is the elapsed time in years for each annual dose [18, 27, 28].

**Chromosome aberration analysis**

*Analysis of dicentrics by solid Giemsa staining*

Blood was taken from the volunteers with informed consent. Heparinised whole blood samples were processed to be cultured within 24 h after collection. The process of culturing, harvesting, staining, and scoring was performed according to previously published technical specifications developed in our laboratory [22, 29, 30], and in accordance with International Atomic Energy Agency (IAEA) recommendations [19]. Metaphase cells were scanned using the Metafer 4 system (MetaSystems GmbH, Altussheim, Germany), and the number of dicentric chromosomes per 1000 metaphase cells was scored.

*Analysis of translocations by fluorescence in situ hybridisation (FISH)*

Cells were harvested and prepared on a slide using the sample protocol in the dicentrics assay. FISH was performed on metaphase spreads using FITC-labeled probes (MetaSystems GmbH) for chromosomes 1, 2, and 4. Chromosomes were counterstained with 4′,6′-diamidino-2-phenylindole. Metaphase cells were scanned using the Metafer 4 system and the number of translocations were counted in 1000 stable cells, that is 360 genome equivalent cells [31]. Age-adjusted translocation frequency was calculated by subtracting age-related background level according to Sigurdson and colleagues’ study [14, 20–24].

**Statistical analysis**

Statistical analyses were performed using SPSS ver. 23 (IBM, Armonk, NY, USA) and Graphpad Prism ver.7 software (Graphpad software, San Diego, CA, USA). As our data do not follow a normal distribution, a non-parametric Mann–Whitney U-test or Kruskal–Wallis test was used to compare chromosome aberration frequencies between different groups. Poisson regression analysis was performed to evaluate the association
between chromosome aberration frequency and occupational conditions, adjusting for potential confounding factors such as age, smoking status, medical radiation exposure, and duration of work. A Pearson scale factor was used to correct overdispersion of the data. To evaluate the correlation between physical recorded dose and chromosome aberration frequencies, a Spearman rank correlation analysis was performed. The statistical significance was set at \( p < 0.05 \).

**Results**

**Study population characteristics**

Descriptive features of the study population are shown in table 1. The study subjects included 120 healthy male industrial radiographers. The age of the workers ranged from 21–52 years with a mean of 36.3 years. The workers, at the time of study, were working as radiographers in South Korea for 8.6 ± 0.6 years (range, 0.21–29.5 years). Their last annual dose measured by personal dosimeter was 1.7 ± 0.4 mSv (range, 0–34.6 mSv), and no subject exceeded the legal dose limit for radiation workers [32]. The mean number of dicentrics per 1000 metaphases (±SEM) and the mean number of translocations per 1000 stable cells (±SEM) were 2.42 ± 0.20 and 4.61 ± 0.31, respectively. The frequencies of chromosome aberrations in radiographers were significantly higher than those in controls, analyzed in a previous study (supplementary figure 1 is available online at stacks.iop.org/JRP/40/151/mmedia).

**Impacts of occupational condition on chromosome aberration frequency**

Table 2 shows the changes in chromosome aberration frequencies according to individual and occupational factors. Translocation frequency increased with an increase in age and duration of work. Workers exposed to radiation for medical and diagnostic tests in the last 3 years had more dicentrics and translocations compared to others.

The association between current radiography workload and dicentric frequency was assessed. Although there was no statistical significance, the dicentric frequency tended to increase as the daily average number of radiographic films used in the last 6 months increased (table 2 and supplementary figure 2(A)). After adjusting for medical radiation exposure in the last three years, the daily average number of radiographic films used was associated with dicentric frequency, as revealed by the Poisson regression model (\( p \)-value = 0.043, table 3). In the last six months, the daily average time of radiography work (another factor to indicate current radiography performance) did not increase dicentric frequency (table 2 and supplementary figure 2(B)). Also, no association with dicentric frequency was observed even after adjusting for confounding factors (data not shown). The inspection workplace is a possible occupational factor that can affect translocation frequency, because radiation protection environment and working behavior of workers can vary based on inspection workplaces. Radiographers performing predominantly enclosure radiography have a lower translocation frequency than subjects performing site radiography. Although there was no statistically significant difference in table 2, we observed that translocation frequency increased with the percentage of site radiography (supplementary figure 3). After adjusting for duration of work, medical radiation exposure in the last three years, and smoking habits, we observed a statistically significant association between the main inspection workplaces and age-adjusted
translocation frequency, calculated by subtracting age-related background level (p-value = 0.009, table 3). A similar association between main inspection workplaces and translocation frequency was observed (p-value = 0.003, supplementary table 1), when age effect was adjusted as a confounding factor in the Poisson regression model as another adjustment method.

Assessment of personal dosimeter-wearing compliance using chromosome aberration frequency

In order to assess personal dosimeter-wearing compliance among industrial radiographers, we investigated the relationship between the dose measured by personal dosimeters and chromosome aberration frequency. Considering the nature of dicentric chromosome and translocation, the correlation between last annual dose and dicentric frequency and between lifetime dose and translocation frequency was analyzed. A strong correlation between recorded dose and chromosome aberration frequency is likely to be observed if the personal dosimeter-wearing practice among subjects is improved. However, there was

| Table 1. General characteristics of the study population. | Industrial radiographers |
|---------------------------------------------------------|--------------------------|
| Age (years)a                                             | 36.3 ± 0.5 (21–52)       |
| Sex, n (%)                                               |                          |
| Male                                                    | 120 (100.0)              |
| Female                                                  | 0 (0.0)                  |
| Smoking status, n (%)                                    |                          |
| Never                                                   | 30 (25.2)                |
| Ever                                                    | 89 (74.8)                |
| Non-responders                                          | 1                        |
| Alcohol intake, n (%)                                    |                          |
| No                                                      | 15 (12.5)                |
| Yes                                                     | 105 (87.5)               |
| Main inspection workplaceb                              |                          |
| Enclosure radiography                                   | 47 (41.2)                |
| Site radiography                                        | 67 (58.8)                |
| Duration of work (years)b                               | 8.6 ± 0.6 (0.2–29.5)     |
| Daily number of radiographic films usedb,c              | 27.7 ± 2.6 (0–100)       |
| Daily time of radiography workb,d                       | 2.8 ± 0.2 (0–8)          |
| Last annual doseb,e                                     | 1.7 ± 0.4 (0–34.6)       |
| Lifetime doseb,e                                        | 33.8 ± 2.8 (0.29–145.5)  |
| Dicentrics frequencyb,f                                 | 2.42 ± 0.20 (0–12)       |
| Translocations frequencyb,g                             | 4.61 ± 0.31 (0–25)       |

a Mean ± SEM (range).  
b Main inspection workplace means where the radiography was mostly carried out. According to workers’ main inspection workplace, they were classified into two groups: enclosure radiography, to perform radiography in shielded enclosures; site radiography, to perform radiography in all other places except shielded enclosures [2].  
c Daily average number of radiographic films used in the last 6 months.  
d The average time to perform radiography throughout the day in the last 6 months.  
e Dose measured by personal dosimeters (mSv).  
f No. of dicentrics per 1000 cells.  
g No. of chromosome 1, 2, and 4 translocations per 1000 stable cells.
Table 2. Chromosome aberration frequency according to individual and occupational factors.

|                      | Dicentric frequency<sup>b</sup> | Translocation frequency<sup>c</sup> |
|----------------------|---------------------------------|-------------------------------------|
|                      | N<sup>a</sup> (%)               | Mean ± SEM p-value<sup>d</sup>     | Mean ± SEM p-value<sup>d</sup> |
| All                  |                                 |                                     |                                     |
| Age (years)          |                                 |                                     |                                     |
| 20–29                | 120 (100.0)                     | 2.42 ± 0.20 0.11                   | 4.61 ± 0.31 <0.001                  |
| 30–39                | 77 (64.2)                       | 2.23 ± 0.27 0.27                   | 3.27 ± 0.26 <0.001                  |
| 40–49                | 30 (25.0)                       | 2.93 ± 0.38 0.38                   | 6.67 ± 0.96 <0.001                  |
| Sex                  |                                 |                                     |                                     |
| Male                 | 120 (100.0)                     | 2.42 ± 0.20 0.11                   | 4.61 ± 0.31 <0.001                  |
| Female               | 0 (0.0)                         |                                     |                                     |
| Smoking status       |                                 |                                     |                                     |
| Never                | 30 (25.2)                       | 2.50 ± 0.48 0.48                   | 4.40 ± 0.74 0.49                   |
| Ever                 | 89 (74.8)                       | 2.40 ± 0.22 0.22                   | 4.69 ± 0.43 0.95                   |
| Alcohol intake       |                                 |                                     |                                     |
| No                   | 15 (12.5)                       | 2.60 ± 0.58 0.58                   | 4.47 ± 1.00 0.005                  |
| Yes                  | 105 (87.5)                      | 2.39 ± 0.22 0.22                   | 4.63 ± 0.40 0.002                  |
| Medical radiation exposure<sup>e</sup> |                                 |                                     |                                     |
| No                   | 85 (72.6)                       | 2.08 ± 0.22 0.22                   | 3.72 ± 0.30 0.005                  |
| Yes                  | 32 (27.4)                       | 3.37 ± 0.44 0.44                   | 6.41 ± 0.82 0.53                   |
| Duration of work (years) |                                 |                                     |                                     |
| Q1 (< 5)             | 32 (26.7)                       | 1.69 ± 0.35 0.35                   | 2.47 ± 0.34 0.006                  |
| Q2 (>=5, <7.5)       | 29 (24.2)                       | 2.45 ± 0.40 0.40                   | 3.62 ± 0.51 0.005                  |
| Q3 (>=7.5, <=10)     | 26 (21.7)                       | 3.00 ± 0.59 0.59                   | 4.92 ± 0.75 0.005                  |
| Q4 (>10)             | 33 (27.5)                       | 2.64 ± 0.29 0.29                   | 7.30 ± 0.88 0.53                   |
| Daily number of radiographic films used<sup>f</sup> | 0.31                            |                                     | 0.53                               |
| Q1 (<=5)             | 30 (27.3)                       | 1.77 ± 0.30 0.30                   | 4.47 ± 0.67 0.005                  |
| Q2 (>5, <=20)        | 30 (27.3)                       | 2.40 ± 0.34 0.34                   | 4.67 ± 0.60 0.005                  |
| Q3 (>20, <=40)       | 28 (25.5)                       | 2.36 ± 0.43 0.43                   | 3.43 ± 0.40 0.005                  |
| Q4 (>40)             | 22 (20.0)                       | 3.00 ± 0.60 0.60                   | 3.64 ± 0.63 0.005                  |
| Daily time of radiography work<sup>g</sup> | 0.61                            |                                     | 0.90                               |
| Q1 (<0.5)            | 27 (25.5)                       | 1.93 ± 0.34 0.34                   | 4.63 ± 0.73 0.005                  |
| Q2 (>0.5, <=2)       | 27 (25.2)                       | 2.63 ± 0.43 0.43                   | 3.85 ± 0.51 0.005                  |
| Q3 (>2, <=5)         | 34 (31.8)                       | 2.50 ± 0.45 0.45                   | 3.91 ± 0.55 0.005                  |
| Q4 (>5)              | 19 (17.8)                       | 2.37 ± 0.39 0.39                   | 4.16 ± 0.59 0.005                  |
| Main inspection of workplace<sup>h</sup> | 0.67                            |                                     | 0.93                               |
| Enclosure radiography| 47 (41.2)                       | 2.47 ± 0.33 0.33                   | 3.98 ± 0.40 0.005                  |
| Site radiography     | 67 (58.8)                       | 2.39 ± 0.28 0.28                   | 4.81 ± 0.57 0.005                  |

<sup>a</sup> Any subjects with missing values were excluded.

<sup>b</sup> No. of dicentrics per 1000 cells.

<sup>c</sup> No. of chromosome 1, 2, and 4 translocations per 1000 stable cells.

<sup>d</sup> Analyzed by a Mann–Whitney U-test or Kruskal–Wallis test.

<sup>e</sup> Medical radiation exposure, here, includes radiation exposure from medical and diagnostic tests in the last 3 years through computed tomography (CT), fluoroscopy, nuclear medicine imaging, nuclear medicine therapy, interventional radiography, and radiation therapy, not considering radiation exposure by plain radiography using x-rays and intraoral or panoramic radiography [25].

<sup>f</sup> Daily average number of radiographic films used in the last 6 months.

<sup>g</sup> The average time to perform radiography throughout the day in the last 6 months.

<sup>h</sup> Main inspection workplace means where the radiography was mostly carried out. According to workers’ main inspection workplace, they were classified into two groups: enclosure radiography, to perform radiography in shielded enclosures; site radiography, to perform radiography in all other places except shielded enclosures [2].
no statistically significant correlation between last annual dose measured by personal dosimeters and dicentric frequency for all workers (table 4). Based on the duration of the radiography-related occupation, only workers in the radiography occupation since 2012 (new workers) showed a statistically significant correlation. Similar results were observed in a correlation analysis with an equivalent acute dose, considering the lifespan of lymphocytes (table 4). In the case of translocation frequency, statistically significant correlation was observed, especially in case of new workers (table 5). Similar results were observed when using age-adjusted translocation frequency. We also observed improved personal dosimeter-wearing compliance in new workers even after adjusting medical radiation exposure (supplementary tables 2 and 3).

### Table 3. Poisson regression analysis between chromosome aberration frequency and occupational condition.

| Response                        | Predictors                                      | N   | β     | Lower  | Upper  | p-value |
|---------------------------------|-------------------------------------------------|-----|-------|--------|--------|---------|
| Dicentrics frequency            | Daily number of radiographic films used^b        | 108 | 0.006 | 0.000  | 0.011  | 0.043   |
|                                 | Medical radiation exposure^c                    |     |       |        |        |         |
|                                 | Yes                                             | 28  | 0.41  | 0.062  | 0.76   | 0.021   |
|                                 | No (reference)                                  | 80  |       |        |        |         |
| Age-adjusted translocation frequency^e | Duration of work                              | 110 | 0.067 | 0.042  | 0.093  | <0.001  |
|                                 | Main inspection workplace^d                     |     |       |        |        |         |
|                                 | Site radiography (reference)                    | 65  | 0.53  | 0.13   | 0.93   | 0.009   |
|                                 | Enclosure radiography                           | 45  |       |        |        |         |
|                                 | Medical radiation exposure^c                    |     |       |        |        |         |
|                                 | Yes                                             | 28  | 0.82  | 0.45   | 1.20   | <0.001  |
|                                 | No (reference)                                  | 82  |       |        |        |         |
|                                 | Smoking status                                  |     |       |        |        |         |
|                                 | Ever                                            | 83  | 0.48  | 0.011  | 0.95   | 0.045   |
|                                 | Never (reference)                               | 27  |       |        |        |         |

^a Any subjects with missing values were excluded.
^b Daily average number of radiographic films used in the last 6 months.
^c Medical radiation exposure, here, includes radiation exposure for medical and diagnostic tests in the last 3 years through CT, fluoroscopy, nuclear medicine imaging, nuclear medicine therapy, interventional radiography, and radiation therapy, not considering radiation exposure by plain radiography using x-rays and intraoral or panoramic radiography [25].
^d Main inspection workplace means where the radiography was mostly carried out. According to workers’ main inspection workplace, they were classified into two groups: enclosure radiography, to perform radiography in shielded enclosures; site radiography, to perform radiography in all other places except shielded enclosures [2].
^e Age-adjusted translocation frequency was calculated by subtracting age-related background level according to Sigurdson et al (2008) [24].
Industrial radiographers had higher dicentric and translocation frequency compared to the control group, which consisted of 120 healthy people never exposed to occupational ionising radiation in our previous study [29]. Workers in this study were exposed to ionising radiation below the legal dose limit, but there was a statistically significant difference in dicentric and translocation frequency when compared with the previously reported control group (the mean number of dicentric chromosomes per 1000 metaphases (±SEM), 2.42 ± 0.20 in workers versus 1.33 ± 0.13 in the control group, p < 0.0001; the mean number of translocations per 1000 stable cells (±SEM), 4.61 ± 0.37 versus 2.61 ± 0.19 in the control group, p < 0.0001). Higher chromosome aberration frequencies in occupationally exposed workers than in the control group have been reported in the literature [8, 18, 26, 33–35]. Although it is unclear whether or how the difference affects the workers’ health, our results suggest that the risk of additional radiation exposure at the workplace in industrial radiography persists despite efforts to protect workers against radiation exposure, such as local shielding, collimation, warning lights, stopping lone working, etc.

### Table 4. Correlation between dose measured by personal dosimeters and dicentrics frequency.

|                               | N<sup>a</sup> | Last annual dose | Equivalent acute dose<sup>b</sup> |
|-------------------------------|---------------|------------------|----------------------------------|
| All                           | 115           | 0.124 (0.19)<sup>c</sup> | 0.16 (0.094)                      |
| Radiographers started before 2012<sup>d</sup> | 81            | 0.047 (0.67)     | 0.022 (0.85)                      |
| Radiographers newly started since 2012<sup>d</sup> | 34            | 0.42 (0.013)     | 0.48 (0.004)                      |

<sup>a</sup> Radiographers who have worked <1 year were excluded in this analysis.

<sup>b</sup> Equivalent acute dose was calculated assuming the half-life of lymphocytes as 3 years (mean life 4.3 years) according to Braselmann et al (1994) and Balakrishnan et al (1999) [18, 27].

<sup>c</sup> Correlation coefficient and p-value analyzed by a Spearman correlation test was shown.

<sup>d</sup> Categorised according to when the workers started to perform radiography: workers who started to perform radiography before 2012 and workers who started to perform radiography since 2012.

### Table 5. Correlation between lifetime dose measured by personal dosimeters and translocation frequency.

|                               | N<sup>a</sup> | Translocations | Age-adjusted translocations<sup>b</sup> |
|-------------------------------|---------------|----------------|----------------------------------------|
| All                           | 115           | 0.44 (<0.001)<sup>c</sup> | 0.42 (<0.001)                          |
| Radiographers started before 2012<sup>d</sup> | 81            | 0.30 (0.006)    | 0.28 (0.012)                          |
| Radiographers newly started since 2012<sup>d</sup> | 34            | 0.47 (0.005)    | 0.57 (<0.001)                         |

<sup>a</sup> Radiographers who have worked <1 year were excluded in this analysis.

<sup>b</sup> Age-adjusted translocation frequency was calculated by subtracting age-related background level according to Sigurdson et al (2008) [24].

<sup>c</sup> Correlation coefficient and p-value analyzed by a Spearman correlation test was shown.

<sup>d</sup> Categorised according to when the workers started to perform radiography: workers who started to perform radiography before 2012 and workers who started to perform radiography since 2012.

### Discussion

Industrial radiographers had higher dicentric and translocation frequency compared to the control group, which consisted of 120 healthy people never exposed to occupational ionising radiation in our previous study [29]. Workers in this study were exposed to ionising radiation below the legal dose limit, but there was a statistically significant difference in dicentric and translocation frequency when compared with the previously reported control group (the mean number of dicentric chromosomes per 1000 metaphases (±SEM), 2.42 ± 0.20 in workers versus 1.33 ± 0.13 in the control group, p < 0.0001; the mean number of translocations per 1000 stable cells (±SEM), 4.61 ± 0.37 versus 2.61 ± 0.19 in the control group, p < 0.0001). Higher chromosome aberration frequencies in occupationally exposed workers than in the control group have been reported in the literature [8, 18, 26, 33–35]. Although it is unclear whether or how the difference affects the workers’ health, our results suggest that the risk of additional radiation exposure at the workplace in industrial radiography persists despite efforts to protect workers against radiation exposure, such as local shielding, collimation, warning lights, stopping lone working, etc.
Our study was the first of its kind to investigate the impact of occupational conditions or working behavior on occupational radiation exposure using individual chromosome aberration frequency. We focused on radiography workload and the inspection workplace as major potential factors that affect radiation exposure to workers. In general, our study suggests that urging workers to complete more radiography assignments in less time to improve efficiency can cause serious safety concerns. A report by the Korean Association for Promotion of Nondestructive Testing suggested that the optimal workload should be restricted to reduce the exposure to ionising radiation as low as reasonably achievable [36]. However, a victim diagnosed with myelodysplastic syndrome in 2011 stated that he worked alone many times and used a maximum of 400 sheets of radiographic films per day [6]. In the present study, we found a statistically significant positive association between dicentric frequency and the radiography workloads in the last six months. This confirms that the increase of radiography workload could enhance radiation exposure. This also suggests that recent radiography workload should be considered in the process of monitoring occupational radiation exposure together with other indicators. Currently, the Nuclear Safety Act has mandated the responsibility to report the workloads of radiographic testing to the NSSC, applicable for clients who request radiography. Further study using the reported data can provide strong evidence to determine a relevant safety guideline.

Radiation exposure levels among industrial radiographers may be affected by different working environments. When working in shielded enclosures, relatively low radiation exposure can be expected. However, site radiography has several challenges like relatively low accessibility to shielding materials, fewer available protective equipment, and limited space, resulting in less control over operational radiation exposure [1, 2]. A recent case report revealed that an industrial radiographer diagnosed with acute radiation syndrome performed radiography several times in offshore plants [5]. In this study, we assessed the difference in translocation frequency based on inspection workplaces. Veteran radiographers are likely to have sufficient experience to perform radiographic testing at various workplaces. Therefore, the duration of work should be adjusted to investigate the impact of inspection workplaces. After adjusting for confounding factors, a statistically significant association between the main inspection workplaces, where the workers mostly carried out the radiography, and translocation frequency was observed. This finding confirmed that site radiography workers can be exposed to a relatively higher dose of radiation than enclosure radiography workers. Our results suggest that additional strategies to protect workers from radiation exposure during site radiography are necessary.

It is important to wear personal dosimeters for estimating accurate exposure dose and managing the work performance and safety of radiographers. However, it was revealed that several radiation workers have poor personal dosimeter-wearing habits. Victims with leukemia induced by occupational radiation exposure stated that they often did not carry personal dosimeters, but reported the dose using dosimeters irradiated artificially [6]. Consequently, a significant discrepancy between dose measured by personal dosimeters and dose estimated by biological dosimetry was observed [6, 7]. We hypothesised that the compliance of wearing personal dosimeters might be different between veteran workers and new workers. A significant correlation between last annual dose and dicentric frequency was observed in the new workers’ group. Translocation analysis also showed similar results: when analyzing the data in new workers, a strong correlation between lifetime dose and translocation frequency was observed compared to veteran or more experienced workers. These findings suggest that new workers have a higher compliance of wearing a personal dosimeter. This observation may be partially attributed to the government’s increased efforts for radiation protection of industrial radiographers since 2012. There is a need to train veteran workers and new workers on the
risk of occupational radiation exposure and appropriate handling of personal dosimeters, in order to improve dosimeter-wearing compliance.

The strong effect of age on translocation frequency has been observed in the literature \[13, 24, 37\] and was adjusted by two approaches in this study: first, we subtracted the expected age-related frequency of translocations from the observed frequency of translocations (table 3); and second, we adjusted for age as one of the confounding variables in the regression analysis (supplementary table 1). The effect of main inspection workplaces (site radiography versus enclosure radiography) on translocation frequency was consistent in both approaches. Medical radiation exposure was also one of the confounding factors that impacted chromosome aberration frequency. Increased cancer risk due to medical radiation exposure remains controversial, but DNA damage after a CT scan is an established phenomenon using the γ-H2AX assay \[38–40\]. An increase of dicentric chromosome frequencies after a single CT scan was also observed in adult patients and pediatric patients below ten years of age \[41–43\]. Similarly, we observed a statistically significant difference in chromosome aberration frequency based on medical radiation exposure history. On the other hand, in another similar study, increased chromosome aberration frequencies due to CT scan/PET examination history in industrial radiographers was not observed \[29\]. This discrepancy may be explained by the different exposure dose range of each subject. Subjects in the study of Jang et al (2016) were high-risk radiography radiographers with relatively higher TLD doses or abnormal complete blood cell count. Their occupationally exposed dose was greater than the dose generally observed for medical purposes; therefore, the effects of CT scan/PET examination history on translocation frequency could not be observed. However, in our study, the population was randomly selected and the exposed dose (33.8 ± 2.8 mSv, range 0.29–145.5) was much lower than that (75.9 ± 3.2 mSv, range 0–418.3) in previous reports. This allows us to observe an increase of chromosome aberration frequencies after medical radiation exposure in our subjects. These findings suggest that the results of cytogenetic monitoring of radiation workers need to be interpreted with caution, considering their medical radiation exposure history.

In the present study, we did not investigate health problems in workers or their relationship with chromosome aberration frequency. An association between the high frequency of chromosome aberrations and increased cancer risk has been shown in epidemiological studies \[44–46\], but the impact of dicentric or translocation among chromosome aberrations on human cancer risk is not fully understood yet. Further studies on radiation-related workers can help assess disease incidence and the health risk of occupational radiation-related-chromosome aberration. Recently, Seo and colleagues launched a prospective cohort study of all Korean radiation workers to assess the health effects related to occupational radiation exposure \[25\]. This kind of cohort study with cytogenetic monitoring can help determine the health risk of increased chromosome aberration in radiographers and confirm hazardous occupational environments in the workplace. Our study consisted of only 120 industrial radiographers, owing to limitations in obtaining sufficient samples of various sub-categories of occupational environments. Therefore, we could not compare chromosome aberration frequencies among different occupational conditions. Further studies with large sample sizes could help identify more specific risk factors in the workplace. More detailed information on major risk factors such as work history in each inspection workplace, recently recorded workload of radiographic testing, and training history of radiation safety for radiographers can help determine radiation safety guidelines for industrial radiographers.
Conclusion

Conclusively, although the health impact of chromosome aberrations observed in workers remains unclear, the fact that cytogenetic markers were affected by their occupational condition and work history suggests that there is a need to improve working environments and carry out additional education on the biological effects of radiation for minimising occupational radiation exposure. Controlling the daily average number of radiographic films used and improving the working environment for site radiography can prove to be effective strategies for radiation protection in workplaces. Lastly, a continuing effort to improve personal dosimeter-wearing compliance is necessary for estimating accurate dose and managing risk by occupational radiation exposure.

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Conflict of interest

None.

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