

Review Article

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Advancements in Biological Dose Assessment for Radiation Emergency Medicine in the Korea Institute of Radiological and Medical Sciences

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Abstract

Accurate radiation dose measurement is crucial for medical intervention and protective actions. Biological dose assessment directly measures radiation-induced molecular and physiological changes, providing information about the absorbed dose and potential health risks. The Korea Institute of Radiological and Medical Sciences (KIRAMS) has performed biological dosimetry using cytogenetic assays since 2010. These assays are used for individual dose estimation in various situations, including occupational exposure, accidental radiation exposure, and health risk assessment of people living near nuclear power plants in Korea. Recent advancements in biological dose assessment methods, such as automated scoring and high-throughput assays, have improved efficiency and enabled more people to undergo dose assessment. The KIRAMS continuously explores new methods and targets for biodosimetry to enhance dose assessment capabilities and can contribute to expand the biological dose assessment capacity with the expertise and facilities, responding to large-scale accidents of radiation exposure in the world.

Radiation exposure due to both industrial accidents, such as nuclear power plant accidents, and dirty bombs used in terrorism or wars is an important increasing concern for human health. In addition, public anxiety has increased regarding radiation use for routine medical purposes such as disease diagnosis and cancer therapy. Accurate measurement of radiation doses in nuclear or radiological accidents is critically important for guiding medical interventions for affected individuals and informing appropriate protective actions. In particular, obtaining precise information through dose assessment is essential for enabling medical staff to plan therapeutic strategies and to separate exposed people for immediate treatment during radiological events.¹ Additionally, evidence has indicated that early dosimetric-guided surgery is highly valuable for prompt surgical intervention for victims before the occurrence of tissue necrosis caused by radiation exposure.² It is difficult to estimate the radiation exposure dose for several reasons, including the diverse types of radiation, the potential inhalation or ingestion of radioactive materials, the distinction between whole-body or partial-body exposure, and the heterogeneity of exposure conditions.³ To mitigate the uncertainties of dose estimates, we have employed multiple methods for dose assessment including biological and physical dosimetry, which can provide complementary and cross-validated data in combination.⁴ Biological dose assessment directly measures molecular and physiological changes in the body caused by radiation exposure. It is a representative method to estimate the radiation exposure dose of individuals and reflects their physiological status. The actual biological damage caused by radiation serves as an indicator of the absorbed dose, enabling the evaluation of potential health risks. This method can supplement the clinical categorization of suspected victims when a personal dosimeter is not available or the extent of a radiation accident is unclear.⁵

Various Techniques Used to Improve the Assay Performance of Biodosimetry

Radiation-induced chromosomal aberrations have been utilized for dose assessment of radiation exposure, grounded in the observation that ionizing radiation causes double-strand breaks in the DNA structure. Residual DNA damage following the repair process can result in a chromosomal aberration. The Korea Institute of Radiological and Medical Sciences (KIRAMS) has performed biological dosimetry using several cytogenetic assays (Table 1). The dicentric chromosome assay (DCA) recommended by the International Atomic Energy Agency (IAEA) and the International Organization for Standardization (ISO) is the gold standard for biological dose assessment.⁶ This method has been well-established and optimized in the KIRAMS since 2010 and is used to estimate the absorbed dose in people with concerns about radiation exposure, including visitors

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Table 1. Biological dose assessments in various studies of radiation exposure

Cytogenetic methods	Study target	Dose range of study	Study features	References
DCA, FISH	Industrial radiographers	103–2235 mGy	Follow-up study for workers reasonably suspected of radiation exposure Calculation of decline rates and the half-lives of frequencies of dicentric and translocated chromosomes 46.9% of the initial frequency in the DCA over follow-up for 18 months	[9]
DCA, FISH	Industrial radiographers	1.7–33.8 mGy	Evaluation study on dosimeter wearing compliance of 120 workers Analysis of the DCA and FISH results with Poisson regression adjusting for confounding factors The frequency in the FISH assay of site-radiography workers was higher than that of workers in a shielded enclosure	[10]
DCA, FISH	Interventional radiologist	203–731 mGy	Case study of a worker with skin cancer Cytogenetic analysis with an in-depth survey of the main interventional work practices High frequency of chromosomal aberrations in fluoroscopy-guided interventional procedures	[11]
DCA	Interventional radiologists Healthy people Industrial radiographers	95–251 mGy	Cytogenetic analysis study of interventional radiologists ($n=52$), lay people ($n=77$), and radiographers ($n=120$) Comparison of dicentric frequency between interventional radiologists and other groups Higher dicentric frequency in the interventional radiologists was associated with partial-body exposure	[12]
DCA (DCScore)	Healthy people Industrial radiographers	0–4000 mGy	Assessment study of a semi-automated scoring method for the DCA using the DCScore program Dose estimation for 39 blind samples and 35 workers using the DCScore and a manual method Approximately 95% accuracy of the semi-automated scoring method for the DCA	[13]
DCA, FISH	Interventional radiologists	250–494 mGy	Case study of 2 workers performed for over 10 years Analysis of multi-aberrant cell types with many dicentric and centric rings (rouge cells) Rouge cell observation for long-term and repeated exposure during working	[14]
FISH	CT-exposed patients	1462–42097 (mGy $\times$ cm)	Comparison study of the translocation frequency of CT-exposed patients ($n=48$) and CT-naïve patients ($n=48$) FISH analysis of the CT-exposed patients compared with the CT dose index and scan length Frequent chromosomal translocation was correlated with cumulative radiation exposure by repeated CT	[15]
DCA, FISH	Breast cancer patients	766–1339 mGy	Follow-up study of breast cancer patients for 1 year after radiotherapy Analysis of the DCA and FISH results focusing on partial-body fractionated radiation exposure Potential use of cytogenetic biomarkers for cancer patients over 1 year after radiotherapy	[16]
MN (MNScore)	Healthy people	0–4000 mGy	Evaluation study on the accuracy of the automated MN scoring method using the MNScore Construction and validation of a dose-response calibration curve for automated MN scoring Dose assessment using the MNScore can be improved by subsequent error correction	[17]

Abbreviations: DCA, dicentric chromosome assay; FISH, fluorescence in situ hybridization; MN, micronuclei; CT, computed tomography

to the accident site of the Fukushima nuclear power plant.⁷ In addition, the regulatory agency for occupational exposure in Korea has asked the KIRAMS to conduct DCA for individual dose estimation of workers suspected of radiation exposure, including approximately 50 workers annually. The accuracy of DCA with a minimum detectable dose of 0.1 Gy, was evaluated based on multiple inter-laboratory comparison exercises to ensure reliable dose assessment⁷. To reduce the scoring time for dicentric chromosomes and enhance the capacity of the DCA, the KIRAMS proposed an advanced method with an automated scoring program for dicentric chromosomes, DCScore (Metafer, USA), which is comparable to the manual DCA in its accuracy, specificity, and sensitivity for dicentric chromosomes.⁸

A fluorescence in situ hybridization (FISH) assay has been also established and used for older or long-term exposure because it recognizes stable translocations, which are persistent and represent more stable types of chromosomal aberrations.⁶ In addition to dose

estimation for occupational exposure using the FISH assay and the DCA in accidental scenarios, the FISH assay with a minimum detectable dose of 0.25 Gy was employed to investigate radiation exposure in people living near a nuclear power plant in Korea. Health risk concerns for residents living near the nuclear power plant have been discussed with various stakeholders, including the nuclear power plant company, governmental regulatory bodies and non-governmental organizations. In 2022, 38 individuals from the resident cohort were examined using a FISH assay, along with undergoing other health risk assessments. Moreover, the KIRAMS also employed the FISH assay to estimate the absorbed doses of 80 defectors from North Korea, who reside near the atomic bomb testing area, while also conducting health examinations in 2023. It is difficult to draw a definitive scientific conclusion regarding whether the defectors were exposed to radiation from atomic bomb testing area based on the investigation. Several uncertainties complicate the interpretation of the findings of the study, including their

residential status, proximity to the testing area, frequency of exposure to atomic bomb tests, and the potential for additional radiation exposure following defection.

Currently, these cytogenetic assays for individual dose estimation are emerging as critical tools assessing the health risk of people after radiation exposure. They can also serve as scientific evidence of radiation exposure in various social and political situations.⁹ The chromosomal aberration dynamics in a group of people in Korea, including industrial radiographers and interventional radiologists, were investigated to assess the working environment and determine appropriate protective measures for occupational radiation exposure.^{10–15} Moreover, these biological dose assessments of the KIRAMS could provide important information for medical exposures such as patients with repeated computed tomography exposure and breast cancer patients undergoing radiotherapy.^{16,17} It can be effectively utilized to estimate an accurate whole-body irradiated dose and assess the biological effects in scenarios involving partial exposure. While diagnostic radiation exposure at relatively low levels is generally considered safe, it raises specific concerns in high-risk population such as pregnancy, infancy, and young women who require mammography.^{18,19} Precise dose information for patients can be used to estimate the health risk associated with medical radiation exposure. Additionally, this information is valuable for evaluating the risks of radiotherapy-induced secondary cancers, thereby facilitating long-term monitoring and management of patients receiving radiotherapy. The cytokinesis-block micronucleus assay, another biological dose assessment method, was improved by the automated measurement of the micronuclei frequencies in binucleated cells for triage in large-scale radiological accidents, overcoming the limitations of the DCA.²⁰

Recently, we have sought to enhance the efficiency of the test through technical advances via new methods, protocols, and biodosimetry targets (Figure 1). These advancements have enabled much more people to undergo biological dose assessment even faster with detection limits of far lower doses. An automated method for measuring of dicentric chromosomes was developed

with data from patients exposed to radiation using a pre-trained deep-learning model.²¹ The implementation of our deep-learning model is expected to significantly reduce the scoring time to approximately 30 minutes per 1 sample, encompassing the analysis of a thousand of cells in DCA. Furthermore, the accuracy in the discrimination of dicentric chromosomes is anticipated to improve progressively through continuous training with millions of images. This model will be employed for practical applications in biological dose assessment by the KIRAMS when further advancements are made and its accuracy and efficiency have been validated. Another approach at test automation involves the development of a high-throughput assay utilizing image flow cytometry. This is a powerful platform that combines the features of conventional flow cytometry and fluorescence microscopy with advances in data processing algorithms. It enables multi-parametric fluorescent and morphological analysis of thousands of cellular events caused by radiation exposure, including gamma H2AX foci formation and micronuclei generation.²² Interestingly, some researchers have reported that DCA when combined with image flow cytometry, significantly enhances the throughput compared to conventional methods.^{23,24} It enables the precise identification of mono- and dicentric chromosomes with high specificity, facilitated by advanced spot-counting algorithms for rare events and sophisticated processing techniques of fluorescent images in the image flow cytometer. It has the potential to further improve the efficiency and throughput of biological dosimetry in the large-scale radiation emergency. We also explored a new target of many biological and medical responses for dose assessment. Extracellular vesicles were reported as potential biomarkers for biodosimetry and showed statistical significance in their correlation with the radiation exposure dose. Extensive experimental data using a disease model suggested extracellular vesicles as a promising candidate for simultaneously estimating the absorbed dose and the risk of disease in people exposed to radiation.²⁵ The KIRAMS has continually refined conventional cytogenetic assays and explored new methods stemming from advancements in biological dosimetry technology.

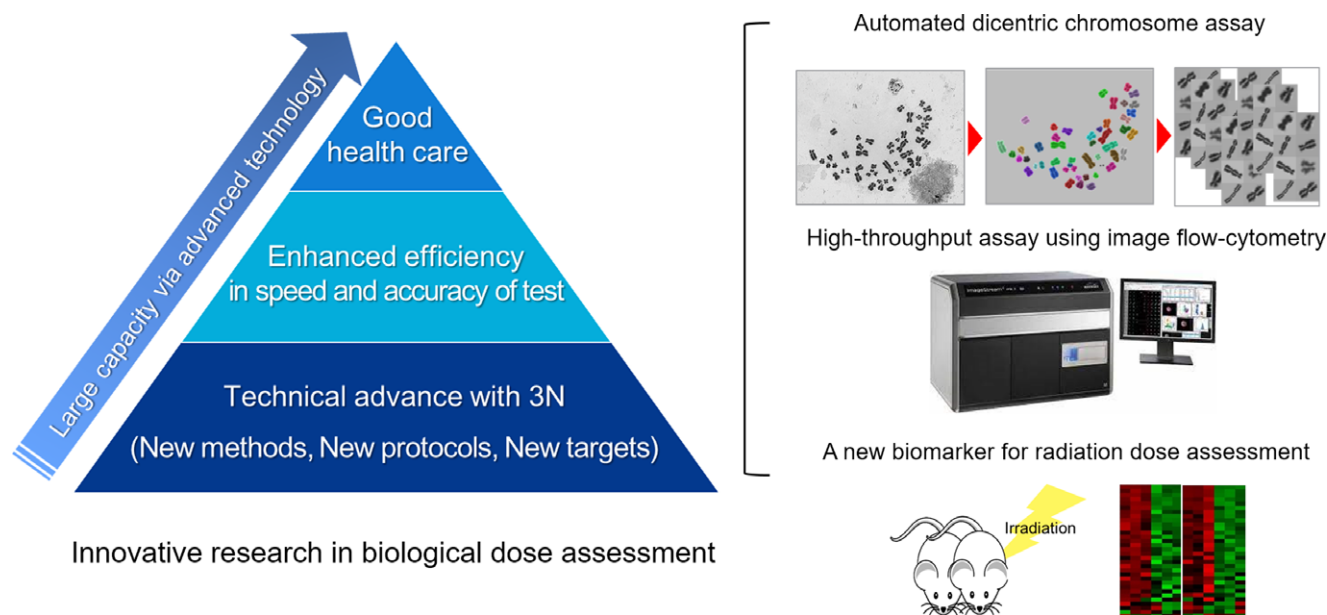


Figure 1. Research to enhance the capacity for biological dose assessment in the KIRAMS. Several technical advancement efforts to enhance biological dose assessment were attempted, including automated analysis using artificial intelligence, high-throughput analysis, and new biomarker development.

Multiple parametric approach in biological dosimetry is useful to assess doses of radiation exposure, particularly in response to radiation emergencies as well as medical treatments.^{26,27} This approach ensures that estimated dose of radiation is both consistent and accurate. Furthermore, it enhances the specificity of biological dose assessment by integrating distinct endpoints, enabling differentiation radiation exposure from other stressors or confounding factors. Such approach is invaluable for tailoring medical treatment and follow-up care for patients exposed to radiation. Regular validation of specificity and accuracy in each method is essential to ensure the robustness of dose assessment.²⁸ Domestic and international inter-laboratory comparison exercises serve as valuable quality control opportunities to maintain high methodological standards. Additionally, cross-validation between different biological dosimetry methods is critical for reliable dose assessment, particularly in complex exposure scenarios.²⁹ It reduces dependence on a single biomarker and facilitates the analysis of individual variation in the biological response of radiation exposure through the use of multiple biomarkers. Several biological dosimetry techniques developed at KIRAMS have the potential to advance efficient protocols for a multi-parametric approach responding to large-scale radiological accidents.

Incorporating Biodosimetry Into the Category of Medical Practice

Both the DCA and FISH assay have been widely employed in cytogenetic techniques for radiation dose estimation using the blood of humans exposed to radiation. These assays were invented to score chromosomal aberrations induced by the DNA damage caused by radiation such as dicentric chromosomes and chromosomal translocations. Unfortunately, these methods are primarily known only to experts in the field of radiation, meaning that the public lacks the knowledge to use these tests without guidance from radiation experts. As a result, there is a clear and practical limitation to the widespread use of these assays. Due to the efforts of the KIRAMS, both assays were officially included in the list of new medical practices of the Ministry of Health and Welfare in Korea in 2016. Additionally, these methods were listed in the National Health Insurance system in 2017, which has distinctive features compared to systems in other countries. The National Health Insurance system offers universal coverage, ensuring that all Korean citizens have access to essential medical services in clinics and hospitals, without restrictions based on specific populations. Anyone seeking biological dose assessment can visit a hospital and ask to take these tests. Therefore, the public can easily undergo biological dosimetry without requiring special permission from the government or authorized institutions helping to alleviate concerns about radiation exposure and radiation-induced health risks. People seeking biological dose assessment can consult with medical doctors regarding their health concerns. Following this, biological dose assessments are carried out by medical specialists in biological dosimetry laboratories upon the request of consulting doctors for visitors to KIRAMS. The costs for medical consultation and practices throughout the process are fully documented and transparently reviewed by the National Health Insurance system. Moreover, excellent medical service related to biological dosimetry can be provided with highly reliable data, thanks to the accreditation of medical testing laboratories by the ISO (ISO 15189) in 2014.¹ Accreditation necessities sustainable quality control and technical management, ensuring high performance in medical tests, including those related to personnel, instruments, facilities, and the environment. The ISO

15189 accreditation for biological dosimetry can aid in decreasing the uncertainty of results, errors, and examination costs, while increasing the reliability of methods, legal validity of results, and global recognition of the data. The laboratory of biological dosimetry in the KIRAMS has obtained certification since 2019 based on its excellent cytogenetics laboratory and referral tests from the Laboratory Medicine Foundation in Korea. This certification serves as a testament to the knowledge and skills necessary to accurately and effectively perform biological dose assessment in laboratory medicine tasks, thereby improving the professional recognition and ensuring quality assurance of data in Korea (Table 2).

Table 2. Capacity building of biological dose assessments in the Korea Institute of Radiological and Medical Sciences

Year	Month	Milestone
2010	May August	Launched the team for dose assessment, consisting of health physics and biodosimetry specialists Testing for radiation workers suspected of radiation exposure as requested by the safety regulation authority
2011	March April	Biodosimetry testing on visitors to the Fukushima nuclear power plant area Opened the laboratory of biological dosimetry
2012	November	First management of a research project regarding biodosimetry in workers with high risk of radiation exposure
2014	December	Acquisition of accreditation for the medical testing laboratory (ISO 15189) from the International Organization for Standardization
2015	November	Participation in the Asian Radiation Dosimetry Group (ARADOS) as a founding member
2016	June	Registration of DCA and FISH as new medical examinations by the Ministry of Health & Welfare in the Republic of Korea
2017	January December	First participation in an inter-laboratory comparison exercise of the RENEB Registration of DCA and FISH in the National Health Insurance system list in the Republic of Korea
2018	June	Registration as a gene testing laboratory by the Centers for Disease Control and Prevention in the Republic of Korea
2019	March	Acquisition of certification as both an excellent testing laboratory and a referral testing site for cytogenetics from the Laboratory Medicine Foundation in the Republic of Korea
2020	March	First execution of a domestic inter-laboratory comparison exercise as a reference laboratory in the Republic of Korea
2022	March August October	Launched the domestic network of Korean Biological Dosimetry (K-BioDos) as a reference laboratory in the Republic of Korea Education and training program development for cytogenetic analysts of biodosimetry in the Republic of Korea Testing of residents near the Wolsong nuclear power plant
2023	March May	Construction of a test referral system for dose assessment in the radiation emergency medicine network in the Republic of Korea Testing of defectors from North Korea who lived near the atomic bomb testing area

Abbreviations: DCA, dicentric chromosome assay; FISH, fluorescence in situ hybridization; RENEB, Running the European Network for Biological and Retrospective Physical Dosimetry

Expanding Assay Capacity for Mass-Casualty Radiation Accidents

The KIRAMS can perform approximately 25 tests per month using conventional biodosimetry methods, analyzing 1000 cells with 5 medical specialists and 3 automatic microscope instruments. Additionally, in radiation emergencies, we can conduct more than 250 tests per week by triage-quality scoring of 50 spreads of cells excluding cell culture and image production.³⁰ In addition to performing triage for dose assessment in accidents, biological dose assessments are essential to relieve the concerns and fears regarding radiation exposure of many people who are unsure whether they have suffered severe damage in a radiation accident. This demand could place a significant burden on our present capacity when using conventional methods. The scoring time of chromosomal aberrations may become a bottleneck in processing a large number of tests in the cytogenetic assay process. Consequently, additional expert scorers are required to assess chromosomal aberrations caused by radiation exposure. To address this issue, we offer an education and training program designed to qualify medical specialists as scorers for radiation-induced chromosomal aberrations. They are required to possess advanced cytogenetic knowledge and high-level skills for analysis of chromosomal aberrations. The program consists of basic and advanced courses. In the basic course, individuals will acquire essential knowledge and understanding of the experimental process involved in cytogenetic assays over a 5-hour period, complemented by 9 hours of hands-on practice with instructors. Then, in the basic course, they undergo intensive training for 8 hours on discriminating and scoring radiation-induced chromosomal aberrations. The advanced course builds upon this foundation, providing 9 hours of instruction on dose estimation equation, measurement uncertainty, operation of instruments and facilities, and medical recording, in addition to the content covered in the basic course. Participants are required to pass qualifying tests at each stage of both courses. Upon successful completion of the basic and advanced courses, medical specialists are fully prepared to conduct biological dosimetry experiments even if they had no prior familiarity with biological dosimetry. This program outlines the essential qualifications required for the staffs involved in biological dosimetry. Continuous training under the supervision of experienced professionals is essential to ensure proficiency in various tasks, including blood extraction, cell culture, slide preparation, chromosomes number measurement, discrimination of chromosomal aberrations and dose estimation. Typically, it takes an additional 6 months of training for a new staff to become competent in applying biological dosimetry in medical practice at KIRAMS.

The KIRAMS is a central authority that controls radiation emergency medicine in a collaborative network including 31 emergency hospitals in Korea.³¹ Unfortunately, most hospitals in the radiation emergency medicine network cannot provide biological dose assessment services after radiation exposure due to a lack of expert staff and specialized instruments and facilities. To address this, we have developed a referral procedure for biological dose assessment to the laboratory of biological dosimetry in the KIRAMS. A practical manual for the referral procedure contains the defined processes for communication, blood sample delivery, requesting examinations, and reporting of results. Medical services for dose assessment in radiation emergencies in Korea can be provided through this system. These procedures can also be applied to individuals who have concerns regarding radiation exposure in their daily life, rather than only in emergency situations.

Although several technical advancements have significantly enhanced capacity for biological dose assessments in the KIRAMS, the methods remain insufficient for a single laboratory to meet the demand for a large number of dose assessment tests. The IAEA has suggested a strategy that involves conducting a large number of tests, which exceeds the capacity of a single biological dosimetry laboratory. This strategy necessitates collaboration with other laboratories within the network and active interactions between the reference laboratory and medical staff. The KIRAMS organized the domestic network of biological dosimetry to enhance the potential of biological dose assessment in Korea. The Korean Biological Dosimetry (K-BioDos) network was established with 4 laboratories in 2022 and grew to 6 laboratories in Korea. The 6 laboratories have various qualification levels for biodosimetry depending on resources available for radiation emergencies. To overcome challenges affecting collaboration and ensure consistent scoring, inter-laboratory comparison exercises are conducted twice a year in the K-BioDos network. These exercises provide opportunities to educate and train our staff through technical meetings and workshops. Moreover, we developed the K-image bank containing numerous chromosome images used in biodosimetry, which were provided by member laboratories. This image bank serves as a valuable resource for technical development and education and training. We have worked to establish a long-term plan for advancing the technical capabilities of biological dose assessment in collaborative responses to radiation emergencies including the construction of a consistent standard curve for dose assessment.

Perspective

The KIRAMS plays a significant role within the World Health Organization Radiation Emergency Medical Preparedness and Assistance Network (WHO-REMPAN), enhancing global health security by preparation to effectively respond to radiation emergencies. This organization contributes to provision of the expertise and resources in medical responses to radiation emergencies. It offers training and enhances the capacity for global medical emergency staff to effectively manage the radiation emergencies. The KIRAMS can provide technical assistance to other countries for radiation emergencies, including radiation monitoring, decontamination, and biological dosimetry. As a reference laboratory in Korea, we can share expertise, resources, and knowledge of biological dose assessment, thereby enhancing collaboration with other states for radiation emergency medicine. For example, our facility can provide chromosomal images to estimate radiation doses according to a standard method,³² and we can estimate the radiation exposure dose from blood samples of victims through referral procedures from requesting countries. In addition, the KIRAMS has participated in international collaborations for biological dose assessment with institutes such as Health Canada, Hiroshima University, and Barcelona University as an individual laboratory and with the Asian radiation dosimetry group (ARADOS) and Running the European Network for Biological and Retrospective Physical Dosimetry (RENEB) as a regional network for biological dose assessment (Figure 2).^{33–36} These types of bilateral or regional cooperation can contribute to standardizing cytogenetic biodosimetry and consequently enhance the capacity for biological dose assessment in global radiation disasters. Furthermore, we currently sought to develop mobile learning tools to offer an education and training program for cytogenetic biological



Figure 2. International collaboration for joint responses in biodosimetry for radiation emergency medicine. An inter-laboratory comparison exercise is a valuable method to enhance joint responses in biological dose assessment for mass-casualty radiation accidents. The KIRAMS has participated in and organized several domestic and international inter-laboratory exercise programs. Samples received from Health Canada in 2019 (A) and the RENEB in 2021 (B) are shown.

dosimetry analysts. We expect that our endeavor to advance biological dosimetry will significantly contribute to improving the preparedness of radiation emergency medicine.

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References

1. Cho M, Seong KM, Park CY, et al. Sustainable medical preparedness and response system for radiation emergencies in the Republic of Korea. *Radiat Prot Dosimetry*. 2018;182(1):20–24. doi:10.1093/rpd/ncy134
2. Lataillade JJ, Doucet C, Bey E, et al. New approach to radiation burn treatment by dosimetry-guided surgery combined with autologous mesenchymal stem cell therapy. *Regen Med*. 2007;2(5):785–794. doi:10.2217/17460751.2.5.785
3. Etherington G, Rothkamm K, Shutt AL, et al. Triage, monitoring and dose assessment for people exposed to ionising radiation following a malevolent act. *Radiat Prot Dosimetry*. 2011;144(1-4):534–539. doi:10.1093/rpd/ncq420
4. Sproull M, Camphausen K. State-of-the-art advances in radiation biodosimetry for mass casualty events involving radiation exposure. *Radiat Res*. 2016;186(5):423–435. doi:10.1667/RR14452.1
5. Pinto MM, Santos NF, Amaral A. Current status of biodosimetry based on standard cytogenetic methods. *Radiat Environ Biophys*. 2010;49(4):567–581. doi:10.1007/s00411-010-0311-3.
6. Dosimetry C. Applications in preparedness for and response to radiation emergencies (2011). Vienna: International Atomic Energy Agency. 229.
7. Lee Y, Jin YW, Wilkins RC, et al. Validation of the dicentric chromosome assay for radiation biological dosimetry in South Korea. *J Radiat Res*. 2019; 60(5):555–563. doi:10.1093/jrr/rrz039
8. Lee Y, Kim SH, Lee YH, et al. Application of a semi-automated dicentric scoring system in triage and monitoring occupational radiation exposure. *Front Public Health*. 2022;10:1002501.
9. Kulka U, Wojcik A, Di Giorgio M, et al. Biodosimetry and biodosimetry networks for managing radiation emergency. *Radiat Prot Dosimetry*. 2018; 182(1):128–138. doi:10.1093/rpd/ncy137
10. Cho MS, Lee JK, Bae KS, et al. Retrospective biodosimetry using translocation frequency in a stable cell of occupationally exposed to ionizing radiation. *J Radiat Res*. 2015;56(4):709–716. doi:10.1093/jrr/rrv028
11. Lee Y, Seo S, Jin YW, Jang S. Assessment of working environment and personal dosimeter-wearing compliance of industrial radiographers based on chromosome aberration frequencies. *J Radiol Prot*. 2020;40(1):151–164. doi:10.1088/1361-6498/ab4686
12. Jang S, Jin YW, Lee WJ. Estimating occupational radiation exposure using cytogenetic dosimetry in an interventional radiologist with skin cancer: a case report. *J Vasc Interv Radiol*. 2020;31(11):1960–1963. doi:10.1016/j.jvir.2020.07.004
13. Lee Y, Lee WJ, Jin YW, Jang S. Interventional radiologists have a higher rate of chromosomal damage due to occupational radiation exposure: a dicentric chromosome assay. *Eur Radiol*. 2021;31(11):8256–8263. doi: 10.1007/s00330-021-07883-0
14. Lee Y, Kim SH, Lee YH, et al. Application of a semi-automated dicentric scoring system in triage and monitoring occupational radiation exposure. *Front Public Health*. 2022;10:1002501. doi:10.3389/fpubh.2022.1002501

15. Jang S, Lee Y, Seo S, Jin YW, Lee WJ. Rogue cell-like chromosomal aberrations in peripheral blood lymphocytes of interventional radiologists: a case study. *Mutat Res Genet Toxicol Environ Mutagen*. 2020;**856**:857–503234. doi:10.1016/j.mrgentox.2020.503234
16. Lee JK, Lee MS, Moon MH, et al. Translocation frequency in patients with repeated CT exposure: comparison with CT-naïve patients. *Radiat Res*. 2019;**192**(1):23–27. doi:10.1667/RR15286.1
17. Lee Y, Kang JK, Lee YH, et al. Chromosome aberration dynamics in breast cancer patients treated with radiotherapy: implications for radiation biodosimetry. *Mutat Res Genet Toxicol Environ Mutagen*. 2021;**872**:503419. doi:10.1016/j.mrgentox.2021.503419
18. Karlsson P, Holmberg E, Lundell M, et al. Intracranial tumors after exposure to ionizing radiation during infancy: a pooled analysis of two Swedish cohorts of 28,008 infants with skin hemangioma. *Radiat Res*. 1998;**150**(3):357–364.
19. Kim E, Boyd B. Diagnostic imaging of pregnant women and fetuses: literature review. *Bioengineering (Basel)*. 2022;**9**(6). doi:10.3390/bioengineering9060236
20. Lee Y, Jin YW, Seong KM, et al. Improving radiation dosimetry with an automated micronucleus scoring system: correction of automated scoring errors. *Radiat Environ Biophys*. 2023;**62**(3):349–356. doi:10.1007/s00411-023-01030-7
21. Kwon SW, Jang WI, Kim M, et al. Discrimination of dicentric chromosome from radiation exposure patient data using a pretrained deep learning model. *Nucl Eng Technol*. 2024;**56**(8):6. doi:10.1016/j.net.2024.03.011
22. Lee Y, Wang Q, Seong KM, et al. High-throughput gamma-H2AX assay using imaging flow cytometry. *Methods Mol Biol*. 2023;**2635**:123–134. doi:10.1007/978-1-0716-3020-4_7
23. Beaton LA, Ferrarotto C, Kutzner BC, et al. Analysis of chromosome damage for biodosimetry using imaging flow cytometry. *Mutat Res*. 2013;**756**(1-2):192–195. doi:10.1016/j.mrgentox.2013.04.002
24. Wilkins RC, Rodrigues MA, Beaton-Green LA. The application of imaging flow cytometry to high-throughput biodosimetry. *Genome Integr*. 2017;**8**:7. doi:10.4103/2041-9414.198912
25. Choi YY, Kim A, Lee Y, et al. The miR-126-5p and miR-212-3p in the extracellular vesicles activate monocytes in the early stage of radiation-induced vascular inflammation implicated in atherosclerosis. *J Extracell Vesicles*. 2023;**12**(5):e12325. doi:10.1002/jev2.12325
26. Tichy A, Kabacik S, O'Brien G, et al. The first in vivo multiparametric comparison of different radiation exposure biomarkers in human blood. *PLoS One*. 2018;**13**(2):e0193412. doi:10.1371/journal.pone.0193412
27. Blakely WF, Port M, Abend M. Early-response multiple-parameter biodosimetry and dosimetry: risk predictions. *J Radiol Prot*. 2021;**41**(4). doi:10.1088/1361-6498/ac15df
28. Wang Q, Lee Y, Shuryak I, et al. Development of the FAST-DOSE assay system for high-throughput biodosimetry and radiation triage. *Sci Rep*. 2020;**10**(1):12716. doi:10.1038/s41598-020-69460-7
29. Shuryak I, Royba E, Repin M, et al. A machine learning method for improving the accuracy of radiation biodosimetry by combining data from the dicentric chromosomes and micronucleus assays. *Sci Rep*. 2022;**12**(1):21077. doi:10.1038/s41598-022-25453-2
30. Lee YH, Lee Y, Yoon HJ, et al. An intercomparison exercise to compare scoring criteria and develop image databank for biodosimetry in South Korea. *Int J Radiat Biol*. 2021;**97**(9):1199–1205. doi:10.1080/09553002.2021.1941384
31. Choi YY, Yoo SY, Yang M, Seong KM. The current safety regulation for radiation emergency medicine in Korea. *Int J Environ Res Public Health*. 2021;**18**(23). doi:10.3390/ijerph182312434
32. Lee YH, Yoon HJ, Yang SS, et al. Lessons on harmonization of scoring criteria for dicentric chromosome assay in South Korea. *Int J Radiat Biol*. 2024;1–6. doi:10.1080/09553002.2024.2316603
33. Barquinero JF, Abe Y, Aneva N, et al. RENEB inter-laboratory comparison 2021: the FISH-based translocation assay. *Radiat Res*. 2023;**199**(6):583–590. doi:10.1667/RADE-22-00203.1
34. Endesfelder D, Oestreicher U, Bucher M, et al. RENEB inter-laboratory comparison 2021: the dicentric chromosome assay. *Radiat Res*. 2023;**199**(6):556–570. doi:10.1667/RADE-22-00202.1
35. Port M, Barquinero JF, Endesfelder D, et al. RENEB inter-laboratory comparison 2021: Inter-assay comparison of eight dosimetry assays. *Radiat Res*. 2023;**199**(6):535–555. doi:10.1667/RADE-22-00207.1
36. Vral A, Endesfelder D, Balazs J, et al. RENEB inter-laboratory comparison 2021: the cytokinesis-block micronucleus assay. *Radiat Res*. 2023;**199**(6):571–582. doi:10.1667/RADE-22-00201.1