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BOOSTER: Development of a Toolbox for Triage of Large Group of Individuals Exposed to Radioactive Material

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Abstract— The effective management of an event involving the exposure of a large number of people to radioactive material requires a mechanism for fast triage of exposed people. BOOSTER is a project founded by the European Union under the Seventh Framework Programme, addressing this requirement. It is a capability project designed to provide an integrated system which could easily be deployed and used. For this purpose, the BOOSTER consortium, relying on the expertise of seven members, researches and develops new approaches to allow an effective and fast management of most kind of nuclear threats. BOOSTER System was designed to help first responders mitigating the crisis by providing the necessary information to quickly assess the radiological situation, to support triage staff in performing an efficient and fast categorization of the potentially affected victims, and to give medical staff crucial information for further treatment at medium or long term post-accident.

Index Terms—Biodosimetry, Crisis management, Nuclear accident, Radiological attack, Triage.

I. INTRODUCTION

Recent nuclear accidents demonstrated people's fear regarding nuclear risks. Moreover, 9/11 attacks showed the reality and impact of terrorist threat which forced societies to quickly adapt and develop new technological solutions. Large scale terrorist attacks or accidental scenarios, involving a radiological risk, could have dramatic and long-lasting consequences from a sanitary but also psychological point of view.

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The effective management of an event involving the exposure of a large number of people to radioactive material, either accidental or following a malevolent use of nuclear material, requires a mechanism for fast triage of exposed people. BOOSTER is a project founded by the European Union under the Seventh Framework Programme, designed to provide an integrated system which could easily be deployed. For this purpose, the BOOSTER consortium developed new approaches to allow an effective and fast management of most kind of nuclear threats. Based on an identified scenario of terrorist attack, reflecting the threats likely to be faced, BOOSTER System was designed to help first responders mitigating the crisis by providing the necessary information to quickly assess the radiological situation, to support triage staff in performing an efficient and fast categorization of the potentially affected victims, and to give medical staff crucial information for further treatment at medium or long term post-accident.

In this paper, an overall description of BOOSTER System functionalities for optimizing crisis management following an accidental or malevolent nuclear event is presented. An emphasis is made on the first results obtained for the adaptation of the GAMPIX gamma camera during laboratory tests. In parallel, summary results of other developments and adaptations is presented allowing a first assessment of BOOSTER performances.

II. ARCHITECTURE OF THE SYSTEM

A. A System Based on Current Procedures

The BOOSTER System architecture was imagined to fit current procedures for radiological crisis management. Once any radiologic contamination is detected on the site of an event, the BOOSTER System is deployed by the first responders. In addition, the necessary command & control echelons are established according to the crisis magnitude.

In the case of the management of a crisis (accident, terrorist attack...), involving nuclear or radiological material, different areas are commonly defined around the scene [1]. These areas are established in order to exclude and guard the dangerous

zone for unauthorized people, protect and control the public, and minimize the spread of contamination in surroundings.

Exclusion area and Controlled Area

The Exclusion area is the area directly affected by the event. It is subject to high levels of radioactivity and contamination. In this area only duly protected first responders perform the rescue and manage the evacuation of the victims. These first responders (mainly firemen) deploy several measurement devices belonging to the BOOSTER System in order to gather crucial information that helps for situation assessment and coming triage. With these components of the BOOSTER System, first responders will provide data on radioactivity levels, taken from deployed sensors, get an overview of the situation, establish the Exclusion area and Controlled area perimeters and guarantee the assessment of the dose received by victims by external irradiation, depending on their position at the moment of the incident.

The Controlled area is a secured area surrounding the Exclusion area. Its perimeter is defined according to the dose rate levels (*i.e.* an area where the dose rate is lower than $0.3 \mu\text{Sv/h}$ according to IAEA guidelines) [1]. The Controlled area is used as a fallback position for the first responders deployed in the Exclusion area and a safer interface for victims evacuation. The first phase of the triage, which consists in a medical triage determining the level of injuries encountered by victims, is carried out in the Controlled area.

Decontamination Area

Before going out of the Controlled area, and in order to minimize the spread of contamination, victims and involved people (members of emergency services, for instance) are taken to a contamination control checkpoint. If a victim is not contaminated, this person can continue the triage circuit. On the contrary, a decontamination process is applied in the Decontamination area, where several measurement devices are deployed to assess the level and the position of external contamination on individuals.

Support Area

Following the decontamination (if required), a deeper analysis of victims for radiological triage is performed once the affected persons arrive to the Support area. This way, the victim triage is accelerated and each person receives adequate treatment according to their radiological status. Those analyses rely on newly developed biodosimetric tools and tests on either biological samples or belongings originating from victims.

Remote Command and Control Area

This area is located away from the event area; nevertheless several command and control components which compose the first echelons are also located in the other usage areas. All information from the Controlled area as well as second level global information from the Support area is received in the Command and Control area and assists the authorities and higher level crisis managers in mitigating the incident effects and manage the available resources in an optimum way.

B. Compactness, Ease-of-use, and Quickness

Due to the particularly difficult work conditions in the affected zone, as explained in the previous section, only duly protected first responders are allowed to operate in this area, the focus is made on the compactness, portability and ease-of-use of the deployed sensors. This portable toolbox allows emergency services to speed up and optimize the first phase of the triage without having to focus their effort toward measurement devices. Therefore, all components were developed or modified in order to be autonomous and easily wearable, or at least easily deployable, by first responders.

In order to speed up the triage process, all in-field analyses were designed to give their results in less than twenty minutes and allow for parallel analyses. As operators carrying out biological samplings (hair follicles, blood, buccal cells...) required for analyses are not necessarily part of the medical staff, sampling material was chosen and especially adapted to be non-invasive.

The software architecture is adapted for use by non-experts. For instance, most sensors are automatized for getting the results and feedback information to upper echelons of command and control by themselves.

C. Coordinated Network and Interoperability

Sensor platforms, including a GPS device were developed to be deployed in the affected area. These platforms were adapted to receive each sensor and have the availability to send the gathered information to a coordinated network based on the SIMACOP system developed by UPV [2]. The core software processes the information from sensors and interpolates to get a picture of the radiological situation in the area of interest. It also provides an evaluation of the exposure and contamination status of people, based on the data from deployed sensors and victims' position in the area.

Information from sensors, estimation from software and data from external sources are processed in a decision support system. This decision aiding component supports users in the triage, taking medical, radiological and resources aspects into account. A module allowing the resource management helps optimizing the strategy of application of the system.

A particular effort was made on the interoperability aspects of the software to easily exchange information with existing National Situation Awareness and Decision Support Systems. This interoperability is supposed to allow the integration of BOOSTER system in the existing crisis management plans and bring accurate information for Authorities of Civil Protection to take informed decisions.

Data transmission between the first level command and control nodes located near the incident site and the second level command and control centers located in a remote location are performed through large bandwidth means (high speed internet connections or satellite).

III. RED ZONE RESPONSE – INFORMING FIRST RESPONDERS

As the first phase of BOOSTER System deployment, a fast evaluation of the radiological situation is performed on the scene with newly developed and adapted existing measurement tools. The fusion of this information with the position of people in the scene allows an estimation of the dose received, may it be by irradiation or by contamination means.

A. A Miniaturized Gamma Camera for Hot Spot Location

As an example of the deployed components, the second generation gamma camera GAMPIX [3], [4], developed by CEA LIST and shown in Fig. 1, was adapted to fit a use by first responders directly in the affected zone. Lightness and compactness of the system are therefore being emphasized along with the system temporal sensitivity.

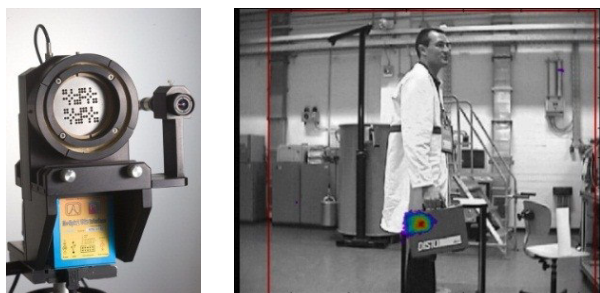


Fig. 1. On the left: current prototype of the GAMPIX gamma camera. On the right: detection of a plutonium sample carried in a piece of luggage.

The principal objective of this gamma camera is to locate the hot spots on the scene so that first responders could be aware of the dangerous areas and avoid them. This application requires, from the camera, to operate in a very large range of dose rates that could be encountered in emergency situations. A characterization of dose rate response of the gamma camera was carried out in a calibration laboratory at Karlsruhe Institute of Technology, Germany. Results on the ^{137}Cs source irradiator showed a good linearity in terms of dose rate assessment from 150 nGy/h to 23 Gy/h.

Specificities of the gamma camera have also been adapted to the type of radionuclides potentially present in a dirty bomb. Measurements with radiological sources of interest for security application were carried out at the Center for Energy Research of the Hungarian Academy of Sciences, Hungary. Results, some of them presented in Fig 2, showed a good applicability of the gamma camera for a wide range of radioisotopes that could be encountered in the frame of a dirty bomb attack or a large scale radiological accident.

Another application that is currently being studied is the detection of contamination spots on individuals to determine which part of the body might have been contaminated. This second field of use requires a good sensitivity to very low dose rates in addition to a good withdrawal of the ambient radiological noise by hardware and software methods. The sensitivity of the gamma camera was shown compatible with such a fast assessment. 150 nGy/h source was imaged in less than 5 minutes

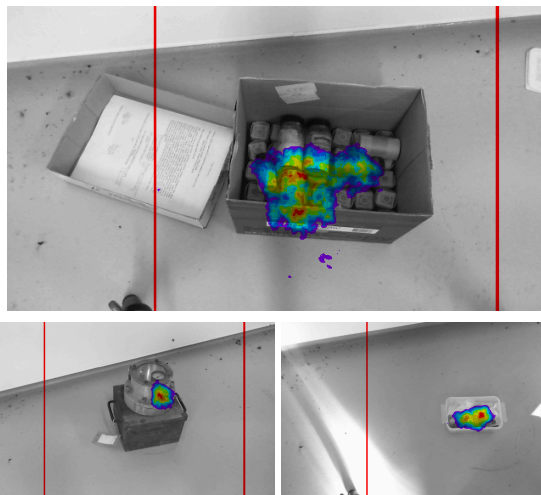


Fig. 2. On the top: uranyl acetate bottles. On the bottom left: plutonium source. On the bottom right: natural uranium bar. Detection duration and sources activities are voluntarily not stated.

B. Network of Sensors for Dose-rate Mapping

In addition to this gamma camera, other sensors were assessed for being deployed over the affected area, allowing the evaluation of the situation. Those sensors, provided by AREVA CANBERRA, include compact dose rate meters equipped with a GPS module for mapping of radiation levels the Exclusion area and portable HPGc detectors for identification of radionuclides faced [5]. Sensor platforms are adapted to each sensor to send the gathered information to a coordinated network based on the SIMACOP system developed by the Polytechnic University of Valencia, Spain. The core software processes the information from sensors and interpolates to get a picture of the radiological situation in the area of interest. Information from sensors, estimation from software and data from external sources are processed in a decision support system providing an evaluation of the exposure and contamination status of people, based on their position in the area.

IV. MITIGATION – INFORMING TRIAGE TEAM

A. A Unique ID for Individuals Identification

Once getting out of the affected area, individuals are given a wristband with a unique barcode ID. This barcode follows the victim during the whole triage process. All analysis results or estimations from sensors are listed under this ID in a specific database that is reachable by triage staff and medical staff at any time for victims follow-up.

B. Tools for Characterization of the Exposure

A complete set of tools was developed or adapted for the characterization of the exposure. The decontamination tents are equipped with cutting-edge detection probes provided by AREVA CANBERRA and allow the determination of the status of individuals and, therefore, the dose received by external contamination.

New, lead and iron, low-background spectrometry systems, developed at the Center for Energy Research were made

compatible with an in-field use. Their design, based on several slices of less than twenty kilograms, allows them to be easily transportable in a van and deployed on the field for direct measurements. According to the first test results, the background radiation is decreased by about two to five magnitudes depending on the energy. Under emergency situation the iron chamber and lead container measurement systems should be used in such a location that the staff can operate the system under safe conditions. Based on these preliminary assessment and first measurements results, applying measurements of a few hundred seconds in such locations would lead to detect the presence of gamma radioactive material being under the exempt activity limit. Those measurements were designed to be carried out on biological samples from victims (urine, saliva, nasal mucus...) to determine the activity of the incorporated gamma-emitting nuclides. By knowing the activity of radionuclides in the body and the approximate time of incorporation, the total dose received can be estimated. First results obtained with the developed low-background spectrometry system, applied to blood with incorporated isotopes, showed the possibility to detect, among others, down to 15 fg of ^{239}Pu , 5 ng of ^{238}U or 35 pg of ^{235}U .

In parallel, investigations on a portable Laser Induced Breakdown Spectroscopy (LIBS) lead to a detection limit of 242 ppm of ^{137}Cs in urine matrix. All together, these measurements allow the determination of the internal contamination of victims, at very low concentrations.

C. New Biodosimeters for Quick Determination of Received Dose

Biodosimetric approaches are frequently focused on cytogenetics. The quantification of the dose from dicentric/ring chromosome scoring appears to be the most precise. Current optimization of such analysis involves the automation of various steps in the process. However, chromosome analyses are performed on the first mitosis post exposure and thus a significant limiting factor remains the culture step of two days that is impossible to reduce. New biodosimeters were developed in the frame of this project to accelerate the triage process.

Irradiation of an individual can be quickly determined by analysis of cellular processes that respond to ionizing radiation effects. Indeed, a major consequence of ionizing radiation is the generation of DNA double-strand breaks [6]. These double-strand breaks induce a rapid and coordinated series of cellular responses, one of which is the phosphorylation of H2AX histone in large chromatin regions (up to 2 Mb) surrounding the break. These regions can be detected by immunofluorescence microscopy as subnuclear foci of phosphorylated H2AX (γH2AX) and the level of γH2AX foci is proportional to the number of nuclear double-strand breaks. Quantification of γH2AX thus allows the determination of the radiation dose received by the cells. However, this H2AX phosphorylation is time-dependent and also depends of individual radio-sensitivity. In order to achieve a new

biodosimetric method, the property of the histone H2AX was used to develop a quick test to determine the level of irradiation of an individual. The test set up takes into account both the variability of the individual sensitivity and the delay for the observation for each individual. The aim is not only to estimate the dose, but also the risk, in order to define preventive actions, appropriate treatments, and subsequent storage place of the victims.

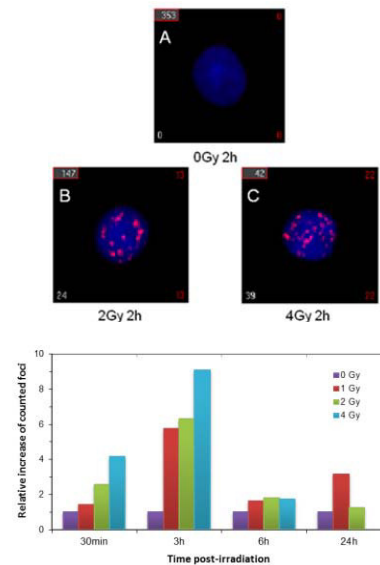


Fig. 3. At the top: follow-up of H2AX phosphorylation in terms of intranuclear foci for irradiation of 0 Gy, 2 Gy and 4 Gy. At the bottom: scoring of phosphorylated H2AX after immunofluorescence microscopy analysis of human lymphocytes exposed to 1 Gy, 2 Gy and 4 Gy.

The Life Sciences Division of CEA tested the proteins extraction on pig hair and human blood which were irradiated at 0 Gy, 2 Gy, 4 Gy and 8 Gy. The phosphorylated histones H2AX (γH2AX) were quantified by labelling or by direct dosimetry of phosphorus with a LIBS system. It appeared that the γH2AX level was proportional to the irradiation doses as shown in Fig. 3.

D. Novel Retrospective Dosimetry on Victim Belongings

The main task of retrospective dosimetry is to assess or, if possible, to determine the absorbed dose posteriorly. Thermoluminescence and optically stimulated luminescence are the most important analytical methods used in retrospective dosimetry. It is known, that natural materials such as sodium-chloride, dolomite or calcite, available in the environment, have luminescence properties and can be used for retrospective dosimetry. On the other hand the subservient luminescence properties of surface-mounted devices (SMD) have also been proved previously suitable for retrospective dosimetry purposes. Environmental materials were selected by the Center for Energy Research, for the investigations in BOOSTER project with respect to the characterization of their luminescence properties. Study focused on the complex characterization and application of SMD resistors for retrospective and accidental dosimetry due to their better properties for the purpose of the project. Consequently thermoluminescence properties and dose response of different

types of SMD resistors were investigated. Several different types of resistors were investigated and measured. First results of dose response of different SMD resistors are presented in Fig. 4.

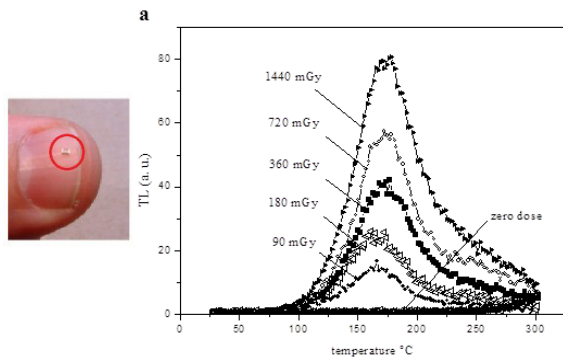


Fig. 4. On the left: picture of a SMD resistor. On the right: thermoluminescence glow curves of 100k type SMD resistor irradiated with different doses

The following parameters of SMD resistors were investigated in the time: thermoluminescence glow curves, dose dependence, reproducibility, fading (stability) and energy dependence. All analysed parameters confirmed the suitability of the SMD devices for retrospective dosimetric purposes. Investigation of other properties (dose rate and temperature dependence, detection limits, etc.) is in progress.

E. Decision Aiding Component for Triage

A software module, developed by the Karlsruhe Institute of Technology, is coupled to the command and control system to help triage teams in their mission and crisis manager to mitigate the situation as quickly as possible. This decision aiding component supports the user in categorising the priority of treatment of individual victims. Factors taken into account can be medical aspects (e.g. trauma patient against radiological exposure), radiological aspects (level of contamination) or resource aspects (number of victims and number of devices). This decision support system is based on the recommendations of the TMT handbook [7].

V. FURTHER FOLLOW-UP – INFORMING MEDICAL STAFF

A. Additional Biodosimetric Tools for Refined Dose

As an additional measure at medium-term post-exposure (hours to days), the scoring of centrosomes duplication will help to confirm quickly the victims triage. The levels of centrosome amplification occurring after irradiation were examined by the National University of Ireland, Galway as a biomarker for exposure [8]. New monoclonal antibodies were developed and characterized to quantitate centrosome number using microscopy and then these reagents applied for biodosimetry.

Irradiation caused a linear increase tendency in both the average number of centrosomes per cell from and in the population of cells with amplified centrosomes, confirming our finding that centrosome amplification is a dose-dependent response to DNA damage, as shown in Fig. 5 and Table 1.

Importantly, this analysis demonstrates that rapid, automated counting is feasible for centrosome quantification as a biomarker. It is also noteworthy that we can feasibly count large numbers of cells using microscopy, allowing improved measurement of centrosome numbers, which we expect to increase the sensitivity of this bioassay.

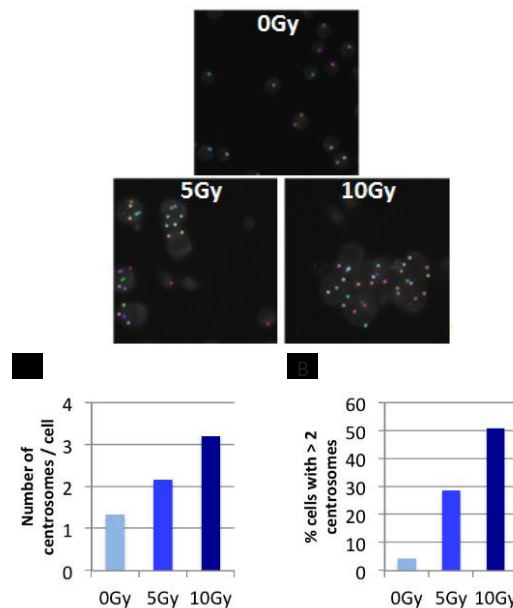


Fig. 5. At the top: counting of amplified centrosomes 24 h after irradiations at 5 Gy and 10 Gy. At the bottom: quantification of centrosome amplification in DT40 cells after irradiation.

TABLE I
NUMBER OF CELLS AND CENTROSOMES INCLUDED IN THE CENTROSOME AMPLIFICATION EXPERIMENT

Irradiation dose	Cells	Centrosomes	Centrosomes per cells	Percentage of cells with more than 2 centrosomes
0 Gy	145596	19473	1.34	4.40
5 Gy	5716	12388	2.17	28.52
10 Gy	8336	26686	3.20	50.87
r^2			0.996	0.999

Cells and centrosomes were imaged and quantified with the Operetta imaging system. The average number of centrosomes per cell (Fig. 5 A) and the percentage of cells with more than two centrosomes (Fig. 5 B) are shown. The increase in average number of centrosomes per cell and in the percentage of cells with amplified centrosomes correlated positively with the radiation dose ($r^2=0.996$ and 0.999 , respectively).

B. Granulometry for Toxicity Assessment

In addition to the radioactivity of the particles, it is essential to determine their granularity and their nature as, independently of radioactivity, toxicity will depend on the nature and the size of the particle. Small sizes are an aggravating factor, by allowing particles to reach more internal organs. The size of the particles is determined using Rayleigh inelastic diffraction or a simple diffraction, obtained by laser interference.

C. Laser Ablation Inductively Coupled Plasma Spectrometry for Analyses of Incorporated Nuclides

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is used for analysis of radionuclides incorporated in body fluids (saliva, blood and urine). Laboratory-based ICP-MS analyses are performed for more precise determination of the dose after the in-field triage. The analytical protocols which were developed by the Center for Energy Research for environmental and swipe samples were re-optimized for overcoming the potential matrix-related interferences during the analysis. Current methods allow the analysis of uranium and transuranium elements in body fluids; the estimated detection limits based on previous experiences on environmental and swipe samples are in the fg/g ($\mu\text{Bq-mBq/g}$) range. The use of special sample introduction methods for direct sampling of solid materials by laser ablation allows extending the analytical capabilities of ICP-MS. Employing this method, the incorporation of elements (heavy metals, platinum group elements, uranium, etc.) can be investigated in the body. The analysis of a single hair with this approach allows the estimation of not only the time of incorporation, but also the change in the incorporated analyte during a given period.

VI. CONCLUSION AND FORESEEN IMPACT

The BOOSTER project focuses on developing new biodosimetric tools and integrating them with state-of-the-art measuring equipment and DSS software in a toolbox. The impact of a dirty bomb attack is well known: considerable disruptive effect, forcing mass evacuations, creating economic chaos, and inflicting environmental and property damage with significant cleanup costs. The outputs of the BOOSTER project are expected to significantly improve the mitigation capability beyond the state of the art and propose new efficient tools for responders on field.

By performing a very fast triage, with newly developed biodosimetric tools and the complete set of radiological sensors, BOOSTER System allows to discriminate very quickly persons who need to be checked carefully from people who have no medical risks. It will also participate to ensuring that people do not overreact to the mere presence of radiation without full knowledge of the extent and type of contamination.

The new measurement tools also allow securing the first responder from the radiation exposure as these tools do not only check the affected people but also provide clear and comprehensive information on the existing contamination level which is far beyond existing radiation equipment available so far.

The prototype of the BOOSTER System was successfully presented during a field trial in May 2013, on KFKI Campus, Budapest, validating the coupling of all devices and showing the applicability of such a system to intended crisis management. It is indeed important to note that even though it was developed for radiological attacks mitigation, the

BOOSTER System is also applicable to the management of major accidents in nuclear facilities or transportation emergencies where individuals involved in the transportation and the nearby population might be exposed immediately.

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