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The 'NOODPLAN' early phase nuclear emergency models: an evaluation

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Abstract

Over the past decades SCK•CEN has developed a set of models –called the NOODPLAN models– for consequence analysis of atmospheric releases during the early phase of a nuclear emergency. All these models use segmented bi-Gaussian plume dispersion algorithms based on the Bultynck-Malet scheme and are limited to a local scale (50 km from the release point).

The different NOODPLAN models are largely customised to the needs of several external users. Customisation includes e.g. source term determination from stack monitoring, connection to on-site meteorological masts, graphic display of countermeasure areas corresponding to intervention guidelines, special modules with standard accident scenarios and specific calculations at the location of detector points (e.g. corresponding to monitoring network). These models have been primarily designed for the Belgian nuclear power plants, the results being used by the radiological evaluation cell of the Federal Crisis Centre, within the framework of the Belgian nuclear and radiological emergency plan. Additional users include research reactors and other nuclear facilities.

The NOODPLAN models perform real time calculations based on variable on-site measured meteorological data, as well as prognostic evaluations. Following a brief description of the different functionalities of the models, this paper will focus on the evaluation of the different NOODPLAN models. This evaluation will draw on our experiences with the NOODPLAN models from regular emergency exercises and will include an inter-model comparison study with state-of-the-art atmospheric dispersion models integrated into the European decision support system RODOS. The results of this evaluation highlight possible future development required to ensure a fast and reliable decision making during the early phase of a nuclear emergency.

Introduction

In a nuclear or radiological emergency the release of radionuclides in the atmosphere can lead to the external and internal exposure of the surrounding population and the contamination of land and water including food products. To estimate the radiological consequences and to initiate the essential countermeasures during an incidental release historically many organisations have developed their own emergency models or systems. Such models combine an atmospheric dispersion part for the calculation of air concentrations and deposition values with a dose model to evaluate the dose from different pathways. Depending on the complexity of the model, the dose from contributions like cloud shine, inhalation, ground shine, ingestion, re-suspension … is calculated.

The NOODPLAN models are a set of models developed for the radiological evaluation of an incidental or accidental atmospheric releases from specific nuclear sites in Belgium. Off-site radiological evaluations up to a few tens of kilometres from the release point by the nuclear operators are a legal requirement in Belgium. The results of the radiological evaluations are sent to the Federal Crisis Centre for further evaluations and decisions on e.g. countermeasures and measurement strategy. Although the NOODPLAN models are historically well established, a regular evaluation and confrontation with the latest developments in the field of nuclear emergency modelling is required. Over the past decade advanced decision support systems with state-of-the-art atmospheric dispersion and dose models have been developed and are increasingly being installed for operational use in national emergency centres. Examples of the main decision support systems for nuclear emergency management used in Europe are ARGOS (Information Management and Decision-Support System for Radiological-Nuclear Hazard Preparedness and Response) and RODOS (Real-time On-line DecisiOn Support system for off-site nuclear emergency management). The evaluation and confrontation of historical models developed for specific sites like the NOODPLAN models with new and generally applicable models can highlight interesting aspects such as the use of specific required model input, model differences and uncertainties (under specific conditions) and possible requirements on future developments for fast and reliable radiological evaluations.

Description of the models

The NOODPLAN models are based on the historical work of Bultynck-Malet [Bultynck H, Malet L, 1969]. During an extensive measurement campaign in the period 1966-1968 using the meteorological mast at the Belgian Nuclear Research Centre (SCK•CEN) an atmospheric turbulence typing scheme with seven stability categories E1-E7 was developed. This so-called Bultynck-Malet categorization is essentially based on the ratio between the vertical gradient of the potential temperature (8m -114m) and the square of the measured mean wind speed at an intermediate level (69m). During the same measurement campaign the appropriate dispersion parameters for each of the stability classes E1-E7 were experimentally determined from wind vector fluctuations in three dimensions measured by means of an anemometer at a height of 69 m. Based on these measurements the dispersion parameters in respectively the horizontal and vertical direction are analytically expressed in function of the distance (x) as $\sigma_y=Ax^a$

and $\sigma_z = Bx^b$ with A, a, B and b depending on the stability category E1 to E7. E1 corresponds to very stable, E3 to neutral and E6 to very unstable atmospheric conditions. E7 is a special neutral category for high wind speed (≥ 11.5 m/s at a height of 69 m). Bultynck-Malet completed these atmospheric dispersion investigations with tracer experiments. In total 15 experiments were executed in which 5 to 6 kg of fluorescent material/experiment was released by an aerosol generator (aerosol dimensions < 4 µm) from the meteorological mast at a height of 69 m and during a release period of ~50 minutes. Air samples were taken at 3 to 7 different locations/experiment at distances ranging from 100 m to 15 km. These experiments showed no significantly nor systematically difference from the calculated values. In addition Bultynck-Malet compared their atmospheric dispersion results with extensive field experiments executed by Brookhaven National Laboratory in better experimental conditions and for a release height near ground level and at 110 m. Due to the better experimental conditions they found even better agreement with these experimental data. More recently the model was confronted with additional limited tracer experiments for ground releases [Govaerts et al., 1988] and stack releases [Rojas Palma et al., 2004]. In both studies the Bultynck-Malet based model performed as good as Lagrangian models.

It can be summarized that the Bultynck-Malet scheme was experimentally well established for hourly values and varying release heights in regions with a rather high surface roughness of 1 to 3 m, applicable in large parts of Belgium and Europe and from distances of a few hundred meters to a few tens of kilometers from the release point.

Based on the Bultynck-Malet formalism different bi-Gaussian plume and even tri-Gaussian puff [Govaerts et al., 1988] models were developed. The formalism was used as well for the development of short duration discharge models for the evaluation of the consequences of accidental releases in nuclear facilities as well as for long duration discharge models for the assessment of routine discharges. The latter evolved to the Immersion Frequency Distribution Model (IFDM) under current development by VITO (The Flemish Institute for Technological Research) which is widely used to calculate the impact of routine releases from industrial facilities [Cosemans et al., 2000]. The Bultynck-Malet (sometimes also called Mol) parameterization is also part of the different parameterization schemes used in the RODOS system.

To overcome the stationary and homogenous situation inherent to Gaussian plume models the NOODPLAN models discussed here make use of the segmented bi-Gaussian plume approach. This makes it possible to treat time-varying releases and transport conditions and especially changes in wind directions. In this approach the plume is broken up into plume segments corresponding to fixed time periods of 10-minutes. To take into account the difference between the original Bultynck-Malet sampling time (30-60 minutes) and the 10-minute periods used in NOODPLAN a correction factor to the dispersion parameters is applied.

The difference between the different NOODPLAN models is the specific customization for the origin of the release. Because the models were developed historically at different moments in time also some –in general minor- differences exist in the modeling aspects. Currently three versions are existing corresponding to a version specific for the Nuclear Power Plants (NPP's) at Doel, at Tihange and the nuclear facilities in the surrounding of Mol (SCK•CEN, Belgoprocess …). All models have the same structure and comprise an input, calculation and reporting module. The input module is highly customized and allows the selection of a specific release pathway (different stacks, steam generator incidents, releases with fire, ground release …) and determines the relative isotopic composition of the different release groups (noble gases, iodine, βγ-aerosols, α-aerosols, tritium) based on the time of release after reactor shutdown. For some of the models automated import of source term data (directly converted from e.g. stack monitoring as well as ventilation rates) and meteorological data is possible. The calculation module allows for the Doel and Tihange systems to add 3 user defined periods with prognostic data. The output module allows printing and visualizing numerical and graphical results. Direct selection of a color scale for the graphical results corresponding to the intervention limits in Belgium is possible. The Doel and Tihange models have in addition a standard scenario module. This is a simple (non-segmented) bi-Gaussian plume model coupled to a database of over 100 standard accident scenarios/reactor. When, based on the technical information available, the best fitting accident scenario is determined this standard scenario module allows doing a first full assessment in less than 1 minute with on-site meteorological data. The models are used by the operators and the results (scenario files) are sent to the Federal Crisis Centre in case of an emergency (or during exercises).

A polar spatial grid is used with a calculation point every 5° on concentric circles with distances from the release point determined by the arithmetic progression with a ratio of $2^{1/8}$ (for Doel and Tihange) and $2^{1/4}$ (for Mol) starting from 200 m up to ~50 km. This gives a very high calculation resolution near the release point while the total number of calculation points is limited resulting in a very short calculation time. Several hundreds additional calculation points can be defined and stored in a database by the users (e.g. detector points corresponding to the environmental monitoring network and points on pre-defined measurement routes) without increasing the calculation time noticeable.

Results

The models are regularly –in general at least two times a year - used during emergency exercises resulting in an important experience in using the models and interpreting the results. Based on the SCK•CEN experience (as utility and operator of the model at the evaluation cell of the Federal Crisis Centre) the following shortcomings can be identified:

- The restriction of the calculation area to around 50 km on several occasions caused problems and confusion regarding intervention limits especially in the case of an important release of I-131. Easy export of all input data available in the NOODPLAN models to a model with an extended range would be interesting.
- The transfer of calculation results from the operator to the Federal Crisis Centre is slow because old technology is used. For this reason the evolution of an emergency –which can easily be calculated with the NOODPLAN models by adding 10-minute periods without the requirement for performing the original calculations again- cannot always be followed continuously. This problem will be solved by using fast data connections in the future.

- Although the definition of additional (detector) points is possible, a direct and fast relation with measurement predictions or results (e.g. combination of dose rate from cloud and ground shine) is missing.
- Although the interface is rather simple, some specific actions of the user are necessary (e.g. specific action for selection and validation of input). This implies the necessity of a regular training (a limited yearly training session seems sufficient) for adequate knowledge of the software.

Further, an evaluation was made by executing an inter-model comparison with state-of-the-art models. Inter-model comparisons are an excellent tool for the assessment of model differences and the uncertainties related to these differences as shown in [Kok et al., 2005]. In this inter-model comparison the Noodplan results are compared with RODOS (ATSTEP) and RIMPUFF results (RIMPUFF within RODOS or a RIMPUFF stand alone version). ATSTEP is a tri-Gaussian puff model with time integrated elongated puffs and employs modified Karlsruhe-Jülich/Mol dispersion parameters applicable for different types of land-use up to a distance of about 100 km from the release point [Pässler-Sauer, 2007]. RIMPUFF is a Lagrangian mesoscale atmospheric tri-Gaussian dispersion puff model developed by Risø (RIsø Mesoscale PUFF model). For RIMPUFF within RODOS the Carruthers sigma-parameters for near range (similarity scaling), and a sigma parameterisation for medium range calculations are used. For the standalone version of RIMPUFF different parameterization schemes can be used but for the calculations performed here similarity-scaling of atmospheric turbulence and diffusion is used in which the calculation of plume spread is based on the basic physical parameters that governs the atmospheric boundary layer turbulence [Thykier-Nielsen et al., 2004].

Both basic scenarios and full realistic scenarios are included in this study. The basic scenarios assume a constant release and constant meteorological conditions for the duration of the plume passage. Nine basic scenarios are defined, starting from a release condition very close to the tracer experiment conditions of Bultynck-Malet, investigating the effect of release height and atmospheric stability under dry conditions. An additional (tenth) basic scenario is defined to evaluate the effect of rain. The scenarios are defined in Table 1. For the RODOS calculations a Cartesian variable grid is selected up to 40 km from the release point with near the release point a grid resolution of 500 m.

Table 1. Definition of the basic scenarios for the inter-model comparison. As well the Pasquill as Bultynck-Malet stability class is specified.

Basic Scenario	Variable parameters			Common parameters
	H_{eff} (m)	Stability	Rain (mm/h)	
1	72	D/E3	0	Release duration: 60 minutes
2-3	1/160	D/E3	0	Released nuclide: I-131 (100% elemental)
4-6	1/74/160	C/E5	0	Total released activity: 6.10^{14} Bq
7-9	1/74/160	F/E1	0	Wind speed= 5 m/s at 72 m
10	72	D/E3	3	No plume rise, no building effects

The complex or realistic scenarios comprise a calculation of a stack release for the Doel site and a release with fire from the Tihange site. Both scenarios consist of a release of 35 periods of 10 minutes, with variable release rates (noble gases, iodine and aerosols) and real meteorological data as typically available on-site (measurements from mast) including periods with rain as well as important changes in all other meteorological parameters. For this study in addition to the NOODPLAN calculations RODOS (ATSTEP) calculations are performed on a variable Cartesian grid with an extension of 80 km from the release point and for the RIMPUFF stand alone calculations with a constant Cartesian grid of 364x364 points with an extension of ~50 km from the release. The models are used at their full complexity for both the basic and complex scenarios. This means that standard land use and topography data are taken into account for the RODOS and/or RIMPUFF calculations. Also the NOODPLAN models are used in the way they are operationally used (i.e. topography used for the Tihange site, not for the Doel site, differences due to different land use is not taking into account in the NOODPLAN models).

The basic results (Time integrated concentration near ground level) for scenario 1 are displayed in Fig. 1. For this scenario the Noodplan results on the plume axis as a function of distance from the release point are compared with RODOS results (ATSTEP as well as RIMPUFF). Clearly visible is the effect of the polar grid with high resolution near the release point of the 'Noodplan' models resulting in a higher value at the position of the maximum. For the other basic scenarios a comparison of 'Noodplan' with RODOS (ATSTEP) is only made at specific distances corresponding with typical distances used for the implementation of countermeasures like sheltering, iodine prophylaxis or evacuation (at position of maximum, 5, 10 and 20 km from the release point). Results for the time integrated concentration as well as the total effective dose are shown in Fig. 2. The total effective dose includes only cloud shine, inhalation and ground shine integrated for 1 week. For the Noodplan models the ground shine for 1 week is calculated based on the value for 24h and 2 weeks (1 week integration time is not a standard output). In general the agreement between the models is very good (in general within a factor 2). For the value at the position of the maximum, the Noodplan results are nearly always higher compared to the RODOS values. This can again be attributed to a difference in spatial resolution near the release point of the two models. The variation of the ratio of the results seems to be somewhat higher for the location at 20 km, compared to 5 or 10 km. The total effective dose is mainly determined by the inhalation dose. The NOODPLAN results are in general higher. If individual exposure pathways are studied the difference is mainly due to a higher contribution from ground shine by the NOODPLAN models.

Results on dry and wet deposition based on scenario 1 and 10 are summarized in Table 2. The difference between the models for deposition (as well dry as wet deposition) is larger then the differences for the air concentration and total effective dose. Differences of a factor 3 to 4 are found here. The Noodplan models show higher deposition values which is explained by a difference in deposition velocities used by the models.

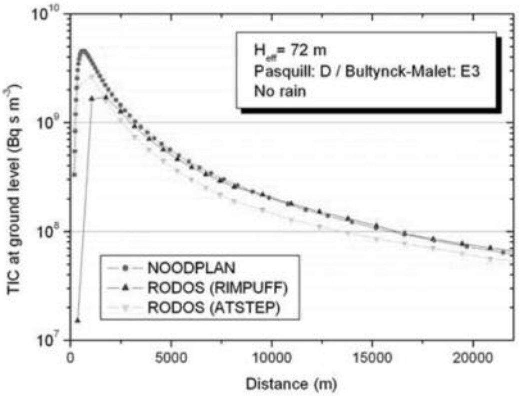

Fig. 1 The Time Integrated Concentration (TIC) near ground level for scenario 1 as a function of distance under the plume axis for the NOODPLAN model compared with the atmospheric dispersion models ATSTEP and RIMPUFF within RODOS.

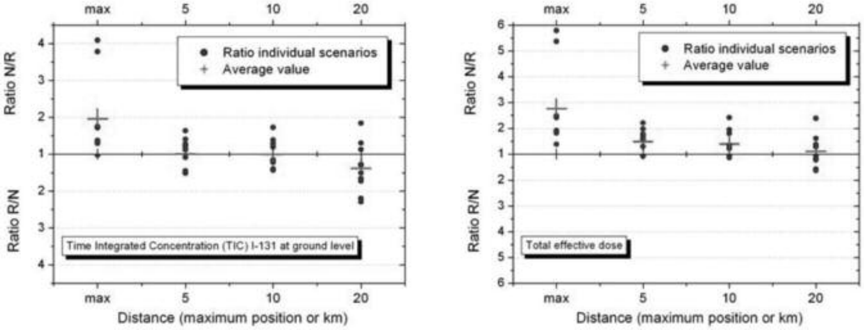

Fig. 2. Results of the inter-model comparison between NOODPLAN (N) and RODOS/ATSTEP (R) for the basic scenarios 1 to 9. On the left site the results of the Time Integrated Concentration are shown, on the right side the results for the total effective dose.

Table 2. Inter-model comparison between NOODPLAN (N) and RODOS/ATSTEP (R) based on scenario 1 and 10 for dry and/or wet deposition of elemental I-131. The dry deposition velocities are derived from the ratio of the deposition to the Time Integrated Concentration at every location. For NOODPLAN this deposition velocity is a constant, for RODOS the value can be dependent on the land use. The difference between the NOODPLAN and RODOS results for the ground contamination is mainly determined by a difference in the deposition velocity (a factor 3).

Distance (max or km)	Dry deposition			Dry+wet deposition
	Ratio N/R	$v_{d,Noodplan}$ (m/s)	$v_{d,\ Rodos}$ (m/s)	Ratio N/R
max	5.07	1.00E-02	3.39E-03	4.99
5	3.61	1.00E-02	3.51E-03	3.00
10	3.94	1.00E-02	3.52E-03	3.28
20	3.27	1.00E-02	3.97E-03	3.22

For the complex scenarios only a qualitative comparison could be made due to differences in the calculation grids used by the models. For the NOODPLAN results a transformation could be made from the standard polar grid to the Cartesian grid selected for the RIMPUFF calculations by a nearest neighbour algorithm. The results for NOODPLAN and RIMPUFF for the most complex scenario with fire and in a complex region (Tihange site in valley of river Meuse) are shown as an example in Fig. 3. The RODOS (ATSTEP) results look very similar. The results for the Doel scenario (stack release, flat terrain) match even somewhat better.

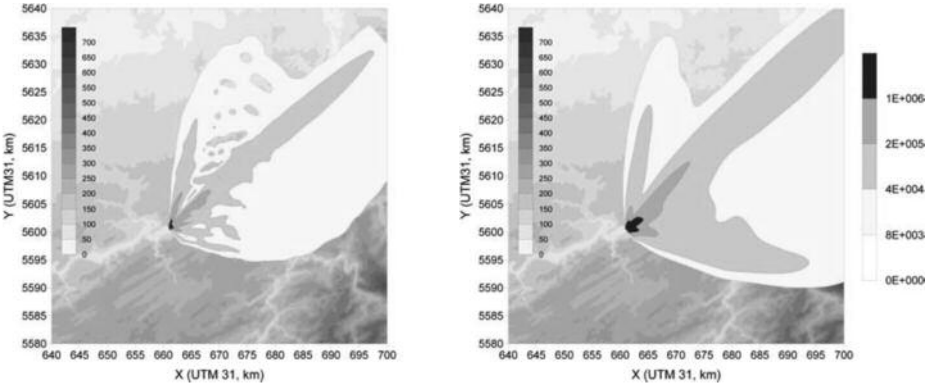

Fig. 3. Time Integrated Concentration (TIC) near ground level of Cs-137 for a release scenario for the Tihange site with fire (35 periods of 10 minutes) for NOODPLAN (left) and RIMPUFF (right) on top of a map showing the topography (height above sea level in meters). The same (color) scale scale for the TIC is used expressed in Bq·s/m^3 in both graphs.

Discussion

Although a good agreement of results in an inter-model comparison is not a guarantee for accurate results due to e.g. common simplifications and assumptions, the execution of inter-model comparisons can identify differences and give confidence in the typical uncertainties present in atmospheric dispersion modelling. Based on this study several interesting observations can be made which highlight possible future developments.

During emergency exercises often the maximal dose or contamination values calculated by the models are used as a starting point for a discussion on the advice of countermeasures. This study clearly illustrates that the maximal value can be strongly connected to grid resolution around this maximum position. A polar grid as used by the Noodplan models has a very high resolution near the release point without having a large number of total grid points. In many scenarios, in which the maximum is within a few kilometres from the release point, this can be seen as an important advantage. However, for specific scenarios with the maximum at several kilometres from the release point the resolution near this maximum will also be limited for the Noodplan models. Most models have fixed grids (or has to be fixed by the user as part of the input data) leading to results in a calculation area and with a resolution which is not always optimal for the interpretation of the scenario under study. The development of routines with flexible and (automated) guidance on grids based on available input and required output seems interesting in this context.

Although the differences in the inter-model comparison in this study for the basic model output (the time integrated concentrations) are small, differences increase clearly for derived parameters like e.g. the ground contamination by dry and/or wet deposition. This increase in difference is only due to the use of different deposition velocities. This shows clearly that good knowledge of basic parameters (such as the deposition velocity) is crucial. Apart from effort in better and more accurate atmospheric dispersion modelling (especially for specific situations like e.g. influence of buildings, urban areas …) a better quantification of basic parameters like deposition velocities seems important. In this respect the confrontation of model results for routine releases with measurements from these discharges in specific regions can be helpful.

Executing inter-model comparisons confronts the user of the models with differences in the required input. The NOODPLAN models are highly customized in a way that all input required by the models is directly related to physical (measured) parameters operationally available on-site. For performing calculations with other models conversions of some parameters have to be done to be able to run these models such as e.g. the parameters for the calculation of the plume rise (specifically for a release with fire). Because the NOODPLAN models are only applicable for the early phase and local scale of a nuclear incident it is interesting to have all input data available for other models. In the new versions of the NOODPLAN models an XML-file with all input data is generated. Concerning the output, a specific module is foreseen to transfer the output files to CSV files for export to a Geographical Information System (GIS).

Although, it is possible in the NOODPLAN models to define a large number of specific calculation points (e.g. detector points) and to display all calculated output for a specific calculation point, fast prediction of or comparison with measurement results is difficult. The development of (scenario preparation) tools for e.g. direct calculation of measurement results in a large number of points (e.g. dose rates, surface contamination, air concentrations) for a number of operationally used detectors would be very interesting.

Simple but highly customized models used by different operators like the NOODPLAN models are under constant evaluation by as well the users (operators), inspectors of the nuclear facilities, and developers. The models are often also used as part of the licensing procedures for the nuclear activities as well as for investigations of routine releases and their impact. In this respect such models are fully complementary to the decision support systems introduced in many European countries the last decade. However, results should be in line and/or differences should be well understood.

Conclusions

This review and evaluation of the NOODPLAN models used as a fast tool to perform radiological impact assessments for the early phase of an accidental atmospheric release from specific nuclear sites in Belgium shows that the results of these models are in line with state-of-the-art nuclear emergency decision support systems installed nowadays by different countries in their emergency centres. The differences found in the inter-model comparison for the basic atmospheric dispersion parameters like air concentrations at ground level are typical smaller than a factor 2-3 even for complex scenarios in large areas of the calculation grid. Derived values such as deposition and dose values differ in general more. This underlines the importance of a good knowledge of the parameters used for the determination of these derived quantities because they determine in a large group of scenarios the main difference between the different models studied here. In addition the polar grid used in the NOODPLAN models showed that the determination of the maximum value of a quantity is less dependent on the gird compared to the grids used for the other models when the location of the maximum is within a few kilometres from the release point. Optimization of grid format, extension and spacing in function of scenario can in this respect be identified as an interesting topic for model developers. The high degree of customization of the NOODPLAN models in combination with (partly automated) input of source and meteorological data validated by the operators during an emergency guarantees the use of as complete and correct as possible data for performing the radiological impact calculations. Because the NOODPLAN models are limited in e.g. range (50 km) and scope (early phase) the export of all input data in a common file structure for use by other models has been identified as an important topic for future development.

References

Bultynck H, Malet L (1969). Diffusion turbulente des effluents émis dans l'atmosphère par une source élevée à émission continue en relation avec la stabilité de l'air. SCK•CEN BLG 434 report (1969).

Cosemans G, Kretzschmar J G (2000). The 1998 IFDM evaluation with the model validation kit. International Journal Environment and Pollution 2000; Vol. 14, Nos. 1-6, pp. 122-130.

Govaerts P, Sohier A, Schorling M (1988). Applicability of Langrangian and Gaussian models for evaluating the consequences of a nuclear accident. SCK•CEN internal report (1988).

Kok Y S et al. (2005). Comparative study of Dutch and German emergency-management models for near border nuclear accidents. Radiation Protection Dosimetry (2005) Vol. 113, No. 4, pp. 381–391.

Päsler-Sauer, J. (2007). Description of the Atmospheric Dispersion Model ATSTEP - Version RODOS PV 6.0 Patch07. Report RODOS(RA2)-TN(04)-03. www.rodos.fzk.de

Rojas Palma, C et al. (2004). Experimental evaluation of gamma fluence-rate predictions from Argon-41 releases to the atmosphere over a nuclear research reactor site. Radiation Protection Dosimetry (2004), Vol. 108, No. 2, pp. 161-168.

Thykier-Nielsen, S., Deme, S., Mikkelsen, T. (2004). RIMPUFF Atmospheric Dispersion Module. Module Description. User Guide. Version 8, revision 103, April 2004. Risø National Laboratory, Roskilde, Denmark.

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Ionizing radiation exposure of the Belgian population in 2006

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Abstract

The radiation exposure of the Belgian population in 2006 was calculated with the methods of the UNSCEAR 2000 report. The annual average effective dose is estimated at 4.6 mSv, of which 2.5 mSv is from natural sources and 2.1 mSv from applications of ionizing radiation; more than 95% from medical imaging. Radiotherapeutic exposures are not accounted for in this overview.

The contribution from diagnostic radiology practice was calculated by multiplying an estimated average dose per type of X-ray examination with the National Health Insurance data on the number of examinations. The exposure is dominated by CT, which provides about 60% of the effective dose; the number of CT-scans increased by 77% between 1997 and 2006 to 155 per 1000 people. An extensive measurement campaign on the patient doses in interventional and cardiological radiology showed effective doses between 5.7 mSv for diagnostic angiography and 15.3 mSv for an average PTCA. The Belgian government has recently launched a project to monitor therapeutic procedures for deterministic effects and to guide optimization in these practices. The effective dose from diagnostic radiology is estimated at 1.88 mSv/y. Better dose estimates will be available after the publication of diagnostic reference levels from the first generalized and legally obliged patient dose survey.

The number of diagnostic administrations of radiopharmaceuticals to patients in Belgium was 52 per 1000 people in 2006 resulting in an effective dose from nuclear medicine of 0.22 mSv/y.The estimated contributions from natural sources in 2006 are the same as in 2001.

The average exposure in Belgium has doubled over the last 110 years, from approximately 2.3 mSv in 1895 to 4.6 mSv in 2006. Of this increase 0.2 mSv comes from natural sources and 2.1 mSv from medical applications. During the same period the average life expectancy in Belgium for man increased from 48 to 77 years and for women from 51 to 83 years resulting in a 3- to 4-fold increase of the lifetime exposure.

The risk perception of the population from ionizing radiation is strongly correlated to the perceived possibility of potential exposure, with a high concern for nuclear waste management and a low concern for medical and natural exposure.

Introduction

Man has always been exposed to natural radiation arising from the earth as well as from outer space (cosmic radiation). Since the discovery of X-rays by Röntgen in 1895 people are also exposed to man-made sources of ionizing radiation. Attention was first drawn to the medical possibilities of diagnosis of bone injuries and imaging of retained bullets received on the battlefield. Diagnostic radiology was in the 20th century supplemented with nuclear medicine and radiotherapy. Outside the medical field industrial and military applications of ionizing radiation were developed, but their collective impact on the population exposure remained limited. Medical uses of radiation continue to increase as techniques develop and become more widely disseminated. As part of this trend, high dose procedures (particularly CT scanning) are increasingly being used to the point that in several countries, including Japan and the USA, medical has displaced natural sources of radiation as the largest overall component of ionizing radiation exposure.

The effective doses to the Belgian population in 2001 were presented at the IRPA 11 conference in Madrid (Vanmarcke 2004) with the methods given in the UNSCEAR 2000 report. In this paper, the assessment is revised using data for 2006.

Medical radiation exposures

Medical imaging has seen the introduction of digital detectors. This has led to 2 main advantages: (1) most detectors can work at a lower dose level than film-screen systems, and (2) digital detectors can be used for new applications, such as high resolution (3D) imaging. This evolution is a logical reply to ever increasing demands for more complex and new imaging procedures and a more efficient use of dose budgets. Next to these arguments, upgrading of technology is governed by financial aspects and work flow issues. Guidance or optimization of dose settings is not yet routine practice in our hospitals. Recent patient dose studies organized in the frame of the medical directive (97/34/Euratom) and its Belgian implementation confirmed a large dose spread.

The amount of radiation per procedure indicates an increasing trend and as a result also the dose to the patient.

- Higher activities can be administered in nuclear medicine to improve image quality. The increasing use of various isotopes with short half-lives, such as technetium-99m (T½: 6 hours), leaves the dose to the patient and the environment within a reasonable margin.
- High doses can be delivered to patients in interventional radiology, sometimes resulting in skin injuries.
- The introduction of digital techniques could reduce the dose provided that the imaging process is strictly controlled. Overexposures that lead to images too dark for interpretation are virtually impossible in digital radiology. The search for better image quality, sometimes introduced without any justification procedure, increases exposure. This is especially the case in CT that has seen the introduction of high resolution cardiac angiography, CT perfusion, dual energy applications, etc..

Very high doses are delivered precisely to tumor volumes in radiotherapy to eradicate disease, mostly cancer, while minimizing the irradiation of the surrounding healthy tissue. The quantity effective dose is inappropriate for characterizing these exposures, in which levels of irradiation are by intent high enough to cause deterministic effects. Radiotherapeutic exposures are therefore not accounted for in this overview. Incidents however have stressed the importance of quality assurance and optimization.

In the frame of these developments, Flemish and Belgian data were collected for the yearly report on the environment and nature in Flanders (MIRA 2007) and were compared to the world average values of the UNSCEAR 2000 report.

Diagnostic radiology

According to National Health Insurance data (RIZIV/INAMI), the average inhabitant of Belgium was subject to 1.2 X-ray examinations in 2006 (excluding dental X-rays) (MIRA 2007). The trend in the annual frequency is shown in fig. 1. The number of examinations remained stable between 1997 and 2006 thanks to efforts of the National Health Insurance to keep the costs under control.

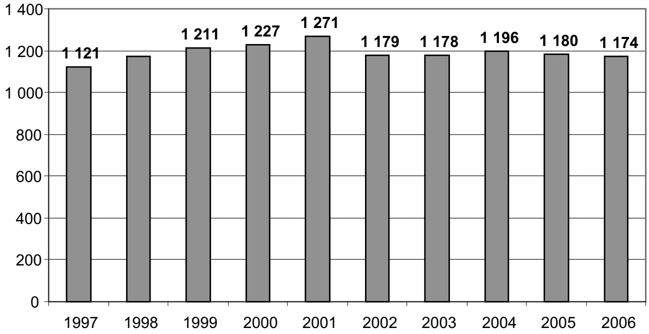
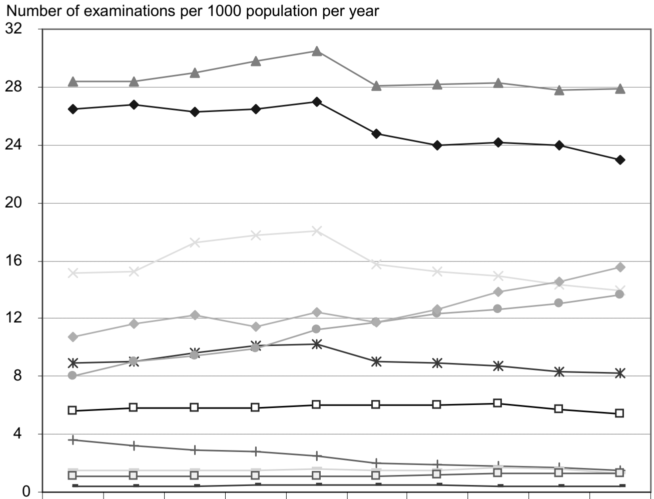


Fig. 1. 10-year trend for total number of X-ray examinations per 1000 inhabitants in Belgium (excluding dental X-rays).

More detailed National Health Insurance data show a shift between the types of examinations (fig. 2). Traditional techniques, such as spine and GI-tract examinations (included in “fluoroscopic examinations”) are being replaced by CT (Computed Tomography) or MR (Magnetic Resonance imaging). The number of CT-scans increased by 77% between 1997 and 2006 to 155 per 1000 people. The figure shows also a significant increase in the use of mammography since 2001, when the Flemish government provided free breast cancer screening for women aged 50 to 69 years. Chest examinations remained constant at a high level. The field of vascular imaging has progressed rapidly over the last decades. Blood vessels are visualized for diagnostic or therapeutic purposes. Diagnostic X-ray procedures are being replaced by non invasive imaging such as MR angiography or CT angiography, but the number of (higher dose) interventional procedures is rising. Vascular imaging should be closely monitored, because the exposure to the patient and the medical team can be very high, especially during interventional procedures. Everyday, doctors improve their skills and knowledge in this field, so that ever smaller vessels or more complex medical problems find a solution. Interventional procedures are considered less risky for the patient than traditional “open” surgery and shorten the duration of hospitalization.



	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
◆ Chest	265.	267.	263.	264.	269.	247.	239.	242.	239.	229.
□ Bed	56.	58.	58.	58.	60.	60.	60.	61.	57.	54.
▲ Limbs and joints	284.	283.	290.	297.	304.	281.	282.	282.	277.	278.
× Head – abdomen – hip	151.	152.	172.	177.	180.	157.	152.	149.	143.	139.
✳ Spine	89.	90.	96.	101.	101.	90.	89.	87.	83.	82.
● Mammography (clin. +	79.	90.	94.	99.	112.	117.	123.	126.	130.	136.5
+ Fluoroscopic examination	35.9	31.6	29.1	27.9	25.2	20.4	19.5	18.5	16.8	15.3
− Arthrography	3.6	3.8	4.2	4.6	5.1	4.6	4.6	4.2	4.2	4.4
− Angiography	14.8	14.9	15.0	15.3	15.8	15.2	15.2	16.6	15.9	13.5
◆ CT	106.8	116.8	122.1	114.6	124.2	117.8	126.1	138.2	145.8	155.2
□ Operating room	10.7	10.8	10.9	10.9	11.5	11.4	12.3	13.1	13.0	13.4

Fig. 2. Trends in diagnostic radiology practice in Belgium between 1997 and 2006 (Bosmans 2007)

As there are only a few data on the doses delivered to patients in radiology in Belgium available, we had to rely partially on data from other sources. The average effective dose per type of examination from four different sources is compared in table 1. In the right column, the effective doses, used for the calculations in the report on the environment and nature in Flanders, are given (MIRA 2007). They were derived from local studies and supplemented by international literature (Bosmans 2007). In Belgium, doses from conventional X-ray examinations are relatively high due to the extensive use of fluoroscopy for positioning of the patient. The selected value for the average CT dose is 7.2 mSv, which is somewhat less than the value from the UNSCEAR 2000 report of 8.8 mSv. The value was calculated from the relative frequency and the effective dose per type of CT examination given in table 2.

The values that were used to estimate the exposure from interventional procedures were retrieved from an extensive national study (Bleeser 2008, Smans 2008, Bogaert 2008). In the frame of this multicenter study, effective patient doses were calculated for diagnostic imaging of the lower limbs and the most frequent cardiac examinations. This study also allowed to estimate effective doses for the other types of frequent examinations. Today, our regulatory authority, the Federal Agency of Nuclear Control, requires that dose data of all dynamic X-ray procedures are registered. How to exploit these data for optimization is not yet clear.

Table 1. Comparison of effective doses from diagnostic X-ray examinations (mSv).

Examination	**UNSCEAR 1993**	**UNSCEAR 2000**	**Mol 2001**	**RIVM 2005**	**MIRA 2007**
Chest	0.14	0.14	0.15	0.07	**0.31**
Limbs and joints	0.06	0.06	..		**0.032**
Spine	1.7	1.8	2.6	0.35	**2.6**
Pelvis and hip	1.2	0.83	..	0.28	**0.83**
Head	0.16	0.07	..		**0.14**
Abdomen	1.1	0.53	0.92	0.45	**0.92**
GI tract	5.7	5.0	..	4.8	**12.9**
Cholecystography	1.5	2.3	..		**2.3**
Urography	3.1	3.7	7.9	3.2	**7.2**
Angiography	6.8	12.0	..	12.2	**Diagn.: 5.7** **Intervent.: 9.8**
PTCA	...	22.0	..		**15.3**
Mammography	1.0	0.51	..	0.4	**0.34**
CT	**4.3**	**8.8**	**7.7**	**1.3 – 11**	**7.2**

Table 2. Average patient dose from CT examinations (MIRA 2007).

Type of CT examination	**Average effective dose mSv**
CT skull	1.5
CT skull base	1.7
CT abdomen and/or chest	12.7
CT spine	5.7
CT limbs and joints including angiography	1.5
Average CT dose	**7.2**

Figure 3 shows the average effective dose distribution of the Flemish population in 2006 from diagnostic X-ray examinations. This distribution is derived from the frequency of the various medical procedures and the average radiation dose for that procedure from table 1 (MIRA 2007). The exposure is dominated by CT, which provides 59 % of the effective dose. The average annual dose from diagnostic radiology in Flanders is estimated at 1.75 mSv in 2006 and in Belgium at 1.88 mSv. The difference is mainly due to a slightly lower number of CT scans in Flanders (142 per 1000 population) than in Belgium (155 per 1000 population).

Figure 4 shows the temporal trends in patient dose from diagnostic radiology in Belgium. The average annual dose from CT increased by 77% between 1997 and 2006. The increase of the CT dose is partly compensated by a decrease in conventional examinations. Most remarkably, the installation of a large number of MR systems has not stopped the expansion of the number of CT examinations.

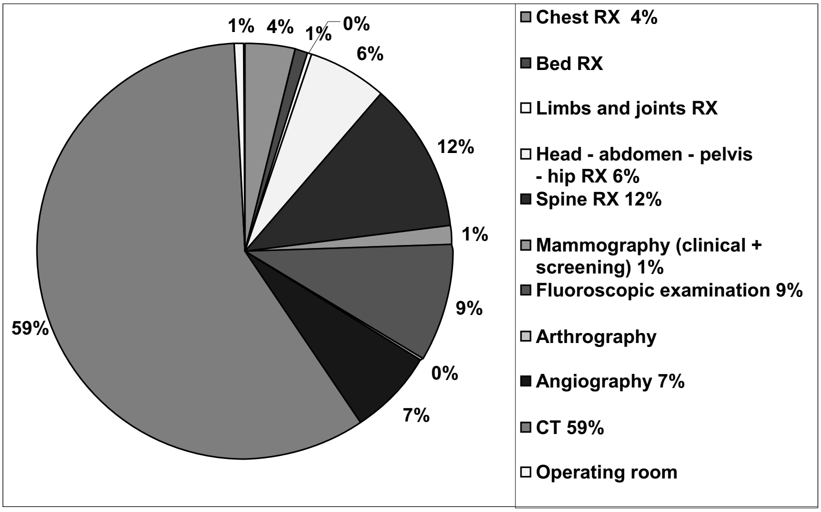


Fig. 3. Dose Distribution from diagnostic X-ray examinations in Flanders in 2006 (Bosmans 2007).

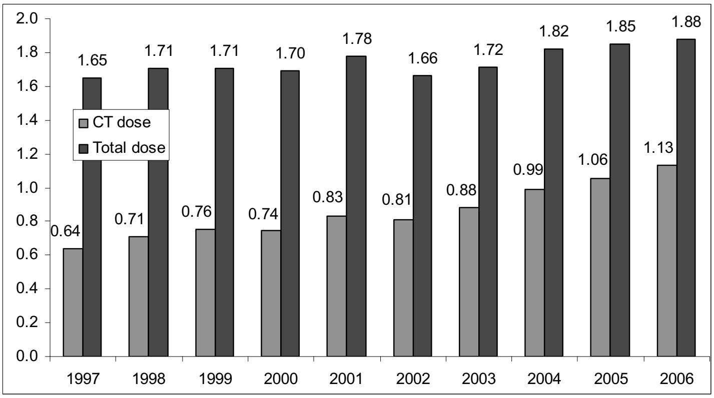


Fig. 4. Trends in annual effective dose (in mSv per year) from diagnostic radiological examinations in Belgium (1997-2006). The large and increasing share from CT is given separately.

Nuclear medicine

In nuclear medicine, radionuclide preparations are administrated to patients for diagnosis or to a much lesser extent for therapy. The number of diagnostic administrations of radiopharmaceuticals to patients in Flanders and Belgium was respectively 40 and 52 per 1000 population per year in 2006 (National Health Insurance data). The large academic hospitals in Brussels, which attract a lot of Flemish patients, could explain the difference. The number of diagnostic nuclear medicine procedures in Belgium is high. The UNSCEAR 2000 estimate for countries with an advanced health care system is 19 per 1000 population per year.

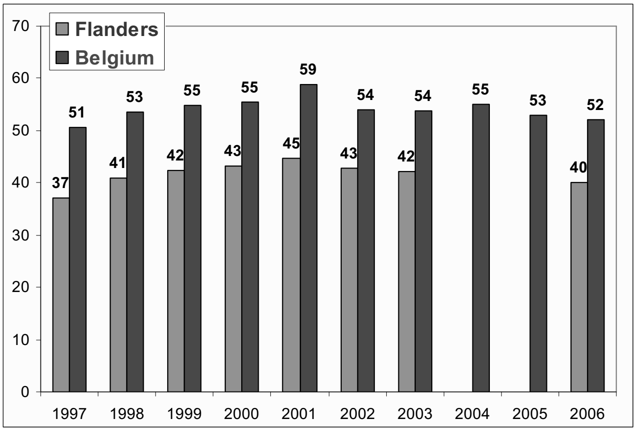


Fig. 5. 10-year trend in diagnostic nuclear medicine practice in Belgium (1997-2006) and Flanders (1997-2003 and 2006).

Positron Emission Tomography (PET), where the radionuclide fluorine-18 (T½: 110 min.) is usually administered in patients, is a relatively new technique, which has proven its value for a number of practices, such as the detection of brain tumors. There are currently several dozen PET scanners in Belgium, including several PET-CT. The dose to the patient from a PET examination varies between 5 and 8 mSv. In case of PET-CT the CT dose has to be added. This CT may be either a full CT, which in most cases replaces another CT, or an examination to improve PET image reconstruction. In the latter case, the dose may be relatively limited. In any case PET-CT is a high dose imaging procedure. A Flemish study showed that technologists who manipulate the F-18 syringes may receive doses to fingers and hands above the limit of 500 mSv/y (Berus 2004).

Technetium-99m dominates the spectrum of the radiopharmaceuticals. The typical dose for an examination is between 1 and 10 mSv and the administered Tc-99m activity between 100 and 900 MBq. The Belgian Society for Nuclear Medicine has published guidelines for the reference administered activities for diagnostic nuclear medicine procedures on their website:

http://www.belnuc.be/images/stories/PDF_guidelines/reference_activities.pdf

A survey at 19 nuclear medicine departments in Flanders estimated the average dose per diagnostic procedure at 4.2 mSv (De Geest 2002). This value, multiplied by the number of examinations in 2006, results in an average dose of 0.17 mSv/y in Flanders and 0.22 mSv/y in Belgium. The corresponding UNSCEAR 2000 estimate for countries with an advanced health care system is 4.3 mSv per procedure and 19 procedures per 1000 population, which corresponds with an average dose of 0.08 mSv/y.

Medical radiation exposures in Belgium in 2006

The average effective dose from diagnostic medical imaging in Belgium in 2006 is estimated at 2.1 mSv/y: 1.88 mSv/y from X-ray examinations and 0.22 mSv/y from nuclear medicine procedures. The corresponding values for Flanders are 1.92 mSv/y: 1.75 and 0.17 mSv/y. The collective medical exposure for the whole population in 2006 is estimated to be:

- Belgium: 0.0021 x 10 511 382 = 22 000 manSv;
- Flanders: 0.00192 x 6 078 600 = 11 700 manSv.

The increasing medical exposure could be responsible for hundreds of excess cancer cases each year in Belgium. It should be noted however that the age distribution of patients differs from the age distribution of the general population on which ICRP-risk coefficients are still based. In digital radiology departments, examination specific age distributions could be retrieved from the image databases, but this is not a routine task in the imaging department.

Exposures from natural radiation sources

The estimated contributions from natural sources in 2006 are the same as in 2001. The average radon concentration in Belgium is estimated indoors at 48 Bq/m³ and outdoors at 10 Bq/m³. With the UNSCEAR dose conversion factor of 9 (nSv/h)/(Bq/m³) (in terms of radon decay products) and a small contribution from radon gas dissolved in blood, a radon dose of 1.35 mSv is calculated. The annual exposure to cosmic radiation is estimated at 0.35 mSv, including a small contribution from air travel and holidays (for instance winter sports). Finally, the external and internal exposures from K-40 and the natural decay series are assessed at 0.4 and 0.3 mSv respectively and the thoron exposure at 0.1 mSv.

Sources and trends of radiation exposure in Belgium

The radiation exposure of the Belgian and Flemish population from natural and man-made sources is compared in table 3 to the average exposure for countries with an advanced health care system from the UNSCEAR 2000 report. The average annual dose in Belgium is 4.6 mSv and in Flanders 4.1 mSv. The largest contribution comes from diagnostic medical examinations, which is estimated, on the basis of social security data, to be 2.10 mSv in Belgium and 1.92 mSv in Flanders. The second largest contribution is from radon exposure.

The average effective dose in Belgium has doubled over the last 110 years from approximately 2.3 mSv/y in 1895 to 4.6 mSv/y in 2006. Of this increase 0.2 mSv/y comes from natural sources and 2.1 mSv/y from medical applications.

- A slow increase of the indoor radon exposure from about 1.15 mSv/y in 1895 to 1.35 mSv/y in 2006. This is due to the reduction in ventilation in modern homes and to the use of building materials with enhanced radium levels, such as phosphogypsum and fly ash. 10 to 100 times higher radon concentrations have been found in some dwellings, mostly located in radon prone areas.
- A small increase of the cosmic radiation of about 0.05 mSv/y from air travel and winter sports. 10 times higher cosmic ray exposures are possible for frequent flyers.
- A strong increase in the medical diagnostic use of ionizing radiation from 0 mSv/y in 1985 to 2.1 mSv/y in 2006. 10 to 100 times higher values are possible for particular patients.
- A small contribution from all other man-made sources of less than 0.05 mSv/y.

During the same period (1895 - 2006) the average life expectancy in Belgium for man increased from 48 to 77 years and for women from 51 to 83 years. The combined effect of these two trends resulted in an increase of the lifetime exposure by a factor of 3 to 4:

- for men from 110 mSv in 1895 to 354 mSv in 2006 and;
- for women from 117 mSv in 1895 to 382 mSv in 2006.

Table 3. Average exposure from radiation sources in Belgium, Flanders and in developed countries with an advanced health care system (Vanmarcke 2004; MIRA 2007; UNSCEAR 2000).

Source	**Average annual effective dose** **Belgium mSv/y**	 **Flanders mSv/y**	 **Worldwide mSv/y**
Natural radiation			
Cosmic radiation	0.35	0.3	0.4
External terrestrial radiation	0.4	0.4	0.5
Radon	1.35	1.0	1.1
Thoron	0.1	0.1	0.1
Internal exposures other than radon	0.3	0.3	0.3
Total (rounded value)	*2.5*	*2.1*	*2.4*
Man-made			
Radiology	1.88	1.75	1.2*
Nuclear medicine	0.22	0.17	0.08*
Other man-made exposures	< 0.05	< 0.05	< 0.05
Total (rounded value)	*2.1*	*2.0*	*1.3*
Total (rounded value)	**4.6**	**4.1**	**3.7**

* Developed countries with an advanced health care system

Risk perception from ionizing radiation

The third risk barometer survey of the perception of the Belgian population (Perko 2010) confirmed that there exists no generalized fear for nuclear activities. Compared to 2006 a slight rise (5%) of risk perception was noticed for most items. Industrial risks (industrial accidents, industrial waste) are evaluated much lower than personal and lifestyle risks. The paradox that the sources with the highest population exposures, such as medical X-rays and natural radiation, are perceived as less dangerous than nuclear power plants, which have a low population exposure in normal operation, continues to exist. However the perception of medical and radon risk is higher than in previous barometers. The risk perception for terrorism, chemical or nuclear waste or accidents was 30 to 40% lower in 2006 compared to 2002. These lower values were for the largest part replicated in the 2009 survey.

The predistribution of iodine for prophylaxis in accidental conditions was widely supported. About 16% of the Belgian population remembers the iodine release incident in August 2008 in IRE, Fleurus. Most people believe the consequences of this release to be more serious than what is communicated by the authorities, and this holds for both the general population and the subset of people who lives near the installation. There remains a significant lack of confidence in the provision of correct information by the authorities on risks related to accidents in nuclear installations or radioactive waste.

Higher confidence exists where authorities have been active and often present in the media.

References

Berus D, Covens P, Buls N, Van den Broeck M, Van Holsbeeck G, Vanhavere F. Extremity doses of workers in nuclear medicine: mapping hand doses in function of manipulation. In: Proc. IRPA 11 congress. 2004 May 23-28, Madrid, Spain. 5f8: http://irpa11.irpa.net/

Bosmans H. Personal communication in the context of the report on the environment and nature in Flanders MIRA 2007.

De Geest E. A multi centre study of the administered activity in nuclear medicine departments in Belgium. Presentation at the EANM congress. 2002 August 31 to September 4, Vienna, Austria.

MIRA Milieurapport Vlaanderen. Achtergronddocument 2007, Ioniserende straling, Vanmarcke H., Bosmans H., Eggermont G., Brouwers J. Vlaamse Milieumaatschappij: http://www.milieurapport.be

Mol H. Dosisinventarisatie radiodiagnostiek in Vlaanderen, VUB study on behalf of the Vlaamse Milieumaatschappij (VMM). Brussel. 2001 (in Dutch).

Perko T, Turcanu C, Schröder J, Carlé B. Risk perception of the Belgian Population: Results of a public opinion survey in 2009. Scientific Report of the Belgian Nuclear Research Centre, SCK•CEN-BLG-1070, Mol, Belgium, 2010.

RIVM Information system on medical applications of ionizing radiation: www.rivm.nl/ims

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. Report to the General Assembly of the United Nations with Scientific Annexes. United Nations publication E.00.IX.3, New York; 2000.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. Report to the General Assembly of the United Nations with Scientific Annexes. United Nations publication E.94.IX.2, New York; 1993.

Vanmarcke H, Mol H, Paridaens J, Eggermont G. Exposure of the Belgian population to ionizing radiation. In: Proc. IRPA 11 congress. 2004 May 23-28, Madrid, Spain. 6d20: http://www.irpa11.com

Bleeser F, Hoornaert MT, Smans K, Struelens L, Buls N, Berus D, Clerinx P, Hambach L, Malchair F, Bosmans H. Diagnostic reference levels in angiography and interventional radiology: a Belgian multi-centre study. Rad. Prot. Dosimetry 2008; 129 (1-3): 50 - 55.

Smans K, Struelens L, Hoornaert MT, Bleeser F, Buls N, Berus D, Clerinx P, Malchair F, Vanhavere F, Bosmans H. A study of the correlation between dose area product and effective dose in vascular radiology. Rad. Prot. Dosimetry 2008; 130 (3): 300-308.

Bogaert E, Bacher K, Thierens H. Interventional cardiovascular procedures in Belgium: effective dose and conversion factors. Rad. Prot. Dosimetry 2008; 129 (1-3): 77 - 82.