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RADIATION RISK AND SCIENCE EDUCATION

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Abstract — Almost everywhere the topic of radioactivity is taught in the physics or chemistry classes of secondary schools. The question has been raised whether the common approach of teaching this topic would contribute to a better understanding of the risks of ionising radiation; and, if the answer is negative, how to explain and improve this situation? In a Dutch research programme which took almost ten years, answers to this question have been sought by means of analyses of newspaper reports, curriculum development, consultation with radiation experts, physics textbook analysis, interviews and questionnaires with teachers and pupils, class observations and curriculum development. The main results of this study are presented and some recommendations given for science teaching and for communication with the public in general as regards radiation risk.

INTRODUCTION

In science classes in senior secondary schools all over the world the topic of radioactivity is taught. The usual approach is to start with the structure of the atom and the nucleus, followed by concepts such as half-life, activity, nuclear fission and fusion. Towards the end of the series of lessons some applications are usually mentioned, such as carbon dating, irradiation and the nuclear reactor. Safety issues are dealt with only superficially.

Such a teaching approach may be defended from the viewpoint that this would be the best way to prepare students for higher education in the sciences. If this proposition is true or not, an objection to the exclusive use of this viewpoint is that nowadays most students in Europe are not in school to prepare themselves for future studies in the physical sciences, but to be educated for life in modern society. One may wonder whether this common approach to teaching the topic contributes to a better understanding of the risks of ionising radiation, a topic often covered in the newspapers and on TV.

In order to explore this field, in the early eighties as part of the large Dutch physics curriculum development project PLON[1] a physics unit was developed which had as its main aim the improvement of student understanding and reasoning abilities regarding the risks of ionising radiation[2]. In this unit a number of safety aspects were added to the traditional nuclear concepts and a great deal of attention was given to medical applications, nuclear arms and the nuclear fuel cycle.

Evaluation showed that such new contents were strongly appreciated by the students (especially the girls), but that their reasoning ability hardly improved. In fact, by asking them to argue about the risks of new applications (such as food irradiation) a number of lay ideas appeared[3] about which, in those days, only limited knowledge was available in the field of science education[4,5]. This was in contrast to other fields of physics, such as mechanics, electricity, light and heat, for which, worldwide, a large number of studies had revealed the existence of lay ideas, more commonly called children's ideas, alternative conceptions or misconceptions[6,7]. These kinds of commonsense ideas which students have before they enter science classes have proved to be rather resistant to change by common teaching strategies in which the existence of these ideas is ignored. However, results were available from risk perception studies[8–10], confirming that many people today hold strong beliefs about the danger of anything nuclear. Weart[11] claims that public ideas in this field are based on a complex web of social and political considerations, on old myths about pollution, cosmic secrets, mad scientists and apocalypse, and on the threat of nuclear war.

As the aim of the PLON materials (improving understanding and reasoning abilities regarding the risks of ionising radiation) had not been achieved satisfactorily, questions were raised about the suitability of the contents of the unit, the role of lay ideas and risk perception, and possible ways to improve the effectiveness of teaching. A study programme was designed to find answers to the following research question:

> 'Which curricular and other teaching conditions must be fulfilled in order to promote thoughtful risk analysis and assessment as regards applications of ionising radiation, through physics lessons in senior high school?'

The main results of this study are presented and some recommendations given for science teaching and for communication with the general public about radiation risks.

OUTLINE OF THE STUDIES

The assumption was made that such an answer could not be given by means of a single study and that the knowledge and experience of radiation experts should be used as one of the bases to improve teaching and learning. It was assumed that radiation experts could advise about:

(i) suitable contents and applications,
(ii) the nature of lay ideas and their consequences for risk assessment, and
(iii) dealing with risk aspects in teaching.

For this purpose a Delphi study[12] was held with 63 radiation experts who worked in a variety of fields: nuclear energy, health care, industry, radiation protection, environment and the civil service. Each expert had at least four years of work experience in his or her field. They completed questionnaires in three rounds, each questionnaire raising issues which could be seen as conclusions from previous rounds.

It was also expected that newspapers would be a source to detect lay ideas about radiation risks. Shortly after the start of collecting newspaper cuttings about ionising radiation, the accident at Chernobyl took place which resulted in an abundance of news reports. For instance, the British newspaper The Guardian carried over 160 separate articles dealing with Chernobyl, as well as several cartoons and over 30 readers' letters. Over 1000 articles from three Dutch (Volkskrant, NRC-Handelsblad and Utrechts Nieuwsblad) and eleven British newspapers (The Times, The Guardian, The Daily Telegraph, The Daily Mirror, The Sunday Mirror, The Sun, The Daily Mail, The Daily Express, The Star, The Sunday Times and The Observer) were collected and analysed.

A third source of information in our research programme was formed by students in secondary schools. Firstly, 312 form IV students completed open questionnaires about Chernobyl, six months after the accident. Next, another thirty form IV students from five different schools were interviewed in depth about their ideas regarding radiation risks around Chernobyl, nuclear waste, medical application, food irradiation and background radiation. Finally, 138 form VI students completed questionnaires after lessons about radioactivity (using traditional or PLON books) testing their insight into radioactivity and ionising radiation.

MAIN RESULTS OF THE STUDIES

Curriculum contents

In the Delphi study general agreement amongst the radiation experts was reached about changes in content of the science syllabus. The way this consensus was reached has been elaborated by Eijkelhof (ch. 2 of Ref. 13). Table 1 presents the subject matter items recommended by the participants as being important for learning to assess the risks of ionising radiation.

Compared with current practices of teaching more attention should be given to contamination with radioactive substances and to basic knowledge about radiation protection.

The participants also agreed on criteria for the selection of a set of applications which should be dealt with in physics lessons. These criteria are:

(1) A large part of the total collective dose should be covered by the set.
(2) Applications which are most likely to be encountered by citizens should be included.
(3) The set should reflect the variety of applications in society.
(4) The applications with the most important social implications should be included.

Table 2 contains the recommendations of the radiation experts regarding the set of applications.

The table shows that to deal with radiation risk it is recommended that a wide variety of applications be used, such as background radiation, medical applications, fallout, storage of nuclear waste and tracer applications in industry and research.

Common lay ideas

In the press reports about radiation issues terms such as 'radiation', 'radioactivity', 'dose' and 'radiation level' are often used. Analysis shows that these reports frequently use these terms with different meanings from those used by scientists[14,15].

A common example is the term 'radiation', which is often used in press reports when scientists would use the term 'radioactive material'; for instance, in quotations such as:

> 'Radiation is still pouring into the air from a fire raging at the plant.'

Table 1. Subject matter items recommended by radiation experts.

A.	*Basic knowledge about atomic and nuclear physics*
	Structure of the nucleus: nucleon, proton, neutron, atomic number, mass number, (Z,N) diagram, isotope, atomic mass unit.
	Radioactive sources: stable and unstable nuclei, energy levels of a nucleus, disintegration, activity (Bq), radioactive decay curve, half-life.
	Ionizing radiation: alpha, beta, gamma and neutron radiation, X rays, nature and properties of these types of radiation, X ray spectrum.
	Detection of radiation: Geiger counter, photographic plate, cloud chamber.
	Nuclear energy: nuclear reactions, nuclear fission, chain reaction, principles of a nuclear reactor.
B.	*Basic knowledge about radiation protection*
	Irradiation: absorption, dose (Gy), interaction with living matter, dose equivalent (Sv), influence of distance and medium.
	Contamination: spreading of radioactive substances in the environment and in the human body.
	Effects of ionising radiation: early and late effects of low and high doses, somatic and genetic effects.
	Safety aspects: film badge, lead apron, radiation norms, ALARA principle, safety measures.

'The wind is carrying the radiation over Scandinavia.'
'Students . . . were contaminated by radiation.'
'We have recently collected examples of fresh standing rainwater and tests showed they contained fairly high levels of short-lived radiation.'

Similarly, the term 'radioactivity' is often applied to situations in which scientists would use the terms 'radiation' or 'radioactive material'.

Related to the lay use of the term 'radiation' is the common idea in the press reports that it is in one way or another conserved after it has entered an object or a person. Examples of this idea are:

'Spinach has been exposed to too much radiation.'
'Radiated crops would not be saleable.'
'In case of a nuclear disaster our water purifying installations could only remove 30 to 50% of the radiation.'

Indeed, the lay idea of radiation makes it impossible to make a proper distinction between situations of irradiation and contamination.

Also related to this is the lack of scientific distinction in news reports between 'activity' and 'dose', for example:

'Accidents at which large doses of radiation are being released.'
'The Germans thought a radiation dose of 1000 Bq acceptable.'
'We need more information about the radiation dose that escaped.'

Both types of terms, of which the latter is most commonly used, seem to indicate a quantity of radiation contained by food, air, water or the human body. In combination with safety levels, they are used to indicate the dangerousness of the situation.

As part of the Delphi study the radiation experts were also asked to formulate lay ideas often found in their professional contacts with the public, to discuss the importance of these lay ideas in view or risk assessment and to participate in the identification of common ideas about the risks of ionising radiation[16]. The lay ideas which the experts most often encountered in their contacts with the public were similar to those found in the news reports. They could be classified according to the lack of insight into the scientific meaning of concepts (such as radiation, radioactive material, contamination, irradiation, activity and dose) and to common ideas about the risks of radiation. Such common ideas are:

(i) radioactivity and radiation are always dangerous (association with cancer);
(ii) radiation for medical purposes is less dangerous than that used for other purposes;
(iii) radiation standards indicate a safety level, safe below, dangerous above;
(iv) a nuclear power station is as dangerous as a nuclear bomb.

According to the participants of the Delphi study some lay ideas have more serious consequences for risk estimation than others. In particular, the importance of the lack of distinction between irradiation and contamination was illustrated with a number of examples from a variety of context domains (Table 3).

These examples show that people are often worried, either too much and sometimes too little, due to their lay conceptions of radiation and risk.

Table 2. Recommended radiation applications for a physics curriculum.

Category I (important)	
1.	Background radiation: from the cosmos, food, rocks, building materials, etc.
2.	Medical applications: diagnostic and therapeutic uses of X rays and nuclear radiation.
3.	Nuclear energy: emission of radioactive substances, normally and after an accident.
4.	Storage of nuclear waste: underground, above ground, on the ocean floor.
5.	Fallout (as a consequence of nuclear weapons explosions).
6.	Some applications of ionising radiation in scientific and industrial research (e.g. tracers).
Category II (fairly important)	
7.	Other industrial applications (materials research, sterilisation, measurement and control).
8.	Immediate consequences of nuclear weapons explosions.
9.	Radioactivity from coal fired power plants.

Table 3. Examples of cases reported by radiation experts.

A.	Reluctance to buy irradiated food for fear of radiation.
B.	The idea that walls of a medical X ray department are full of radiation and therefore should be treated as radioactive waste.
C.	Some workers who look after animals which are irradiated by X rays in experimental settings had a feeling of being neglected: they had not been issued dosemeters and did not get regular blood tests in contrast to personnel who irradiate the animals, although the latter personnel had less contact with the animals.
D.	A nurse who does not place herself behind a wall when taking X rays because 'the radiation would reach me anyhow through the open door'.
E.	The social isolation of an industrial worker who received an extra radiation dose by accident: he was considered by his colleagues and neighbours to be suffering from radioactive contamination.

Students' ideas

The interviews with students focused on their ideas about radioactivity, ionising radiation and risk in the contexts of Chernobyl, medical use of radiation, radioactive waste disposal, food irradiation and background radiation. Students' ideas within these contexts show that commonsense and information from the media dominate many of the students' views. Scientific notions play a small or non-existent part. Reasoning appears to be centred around the perceived risk of radiation for people. The nature of the effects of radiation is quite well known and does not differ from context to context, in spite of the perceived seriousness of the radiation hazard in each context.

Students seem to be less concerned with the nature and origin of the radiation. They often make analogies. These analogies are based on the characteristics of the contexts, especially the function of radiation and the saliency of safety measures. Propagation of radiation is only seen as relevant if the source is at a large distance and is considered dangerous (for example, Chernobyl and radioactive waste). When sources are nearby and inside buildings (for example, food irradiation, health applications and radon from building materials), ventilation is considered to be useful. The scientific notion of absorption was seldom found.

Students seem to have conservation ideas about radiation, which could be summarised as: 'When an object (such as food or a wall) receives radiation, the radiation will accumulate in the object. When the amount of radiation is large enough, the object will itself start emitting radiation'.

Students also appear to attribute meanings to the terms 'radiation', 'contamination', 'radiation standards' and 'radioactivity' which differ from the accepted scientific meanings.

Indiscriminate use of the terms contamination and irradiation was very common. Many students spoke of contamination when someone or something has received a certain amount of radiation, sometimes specified as 'a surplus' of it or 'more than normal'. Analysis of the answers also showed that students seem to have different meanings for 'radiation standards'. Four distinct views were recognised:

(1) A *regulation* view, expressing the idea that standards are what the regulatory bodies consider to be acceptable. This would apply to contamination of food and air, and to irradiation of people.
(2) A *threshold* view suggesting that there will be zero risk below a certain standard level. The body is expected to be able to cope with small amounts of radiation.
(3) A *probabilistic* view in which the risks are seen as more or less directly proportional to the received dose. Below the standards the risk is generally seen as small.
(4) A *distrust* view. Standards are seen as meaningless as all radiation is dangerous.

Finally, in the interviews forms of reasoning were identified which were labelled 'commonsense reasoning'. Students draw conclusions which seem logical to them because the conclusions are based on the uses of radiation, on personal experience or on the existence of safety measures or protests about safety. Examples of such reasoning are:

> 'If you look at how the workers in a food irradiation plant have to be protected with special clothing, it could not be right for an apple to receive a dose of radiation.'
> 'Food irradiation is not dangerous, otherwise they wouldn't do it'.'

A number of the lay ideas found with students appeared to persist despite instruction. Table 4 lists those lay ideas which were found with a majority of the senior secondary students after several weeks of instruction on the topic of ionising radiation.

No significant difference in the presence of these lay ideas was found between the PLON students and the students who worked with traditional books. In both learning materials no attention was given to the existence of lay ideas. Apparently, teaching the topic of ionising radiation without paying attention to lay ideas has little effect on students in altering those ideas.

RECOMMENDATIONS

The results about lay ideas appear not only to apply to Dutch students but have been confirmed in England[17–19], Norway[20] and Poland[21].

The studies described in this paper have led to conclusions which should have consequences for science education. If the main aim of science education in secondary schools should be to prepare students for coping with life in modern society, the purpose of teaching the topic of ionising radiation should be shifted from

Table 4. Examples of persistent lay ideas.

A.	Radioactive contamination means that someone is contaminated with radiation.
B.	The period in which nuclear radiation from an external source remains active in a cancer patient depends on half-life or length of irradation.
C.	Radiation might accumulate in the human body.
D.	After an accident in a nuclear power station, the radiation might be spread by the wind.
E.	Radiation might be stored in food which is irradiated, so it is dangerous to eat that food for some time.
F.	X rays have effects on the human body which are very different from those of nuclear radiation.
G.	X rays should be extracted from air in order to reduce radiation risks.

'understanding nuclear physics' towards 'being able to understand radiation risk information'. This should have effects on curriculum contents and teaching strategies. Such changes are not easily implemented: it requires changes in current practices of teaching which could be characterised as (i) focusing on closed sources and on processes in the nucleus, (ii) paying low attention to risk concepts, (iii) using a limited range of applications, and (iv) ignoring the role of lay ideas and lay ways of reasoning. In our experience, support from the field of radiation experts could be very helpful in this respect.

One should acknowledge, however, that this is a sensitive issue. Some teachers might fear that radiation experts want to trivialise radiation risks or to prescribe ways of teaching. The basis of cooperation should be formed by a common goal: making science education more relevant and interesting for students. Input from the teachers into such cooperation is their teaching experience with the age group and their knowledge of the curriculum. Input by the radiation experts should be their knowledge of the radiation field as regards contents and applications. Synthesising both types of expertise could be very fruitful and of benefit for a large number of young people.

What could be learned from our studies for radiation risk communication in general? One should realise that the public has a lot of knowledge and beliefs about radiation risks which in the experts' view may be wrong and inconsistent, but which are not so perceived by the audience. The public's ideas have served them well so far(22,23) and could well be interpreted in a coherent way(24,25). Any risk communicator should be familiar with the general public's ideas, and try to understand the meanings which are commonly ascribed to terms. It is likely that communication with the public is more effective when it starts from the common knowledge base of lay people and experts(25).

Of course, the best way to communicate about radiation risk depends on the audience. When dealing with lay people, it may be wise to avoid unnecessary use of micro-meanings of concepts such as radiation, activity, dose and half-life. Macro-interpretations of these concepts are usually sufficient and are better understood by many people(25,26). It is also advisable to emphasise the distinction between irradiation and contamination, and open and closed sources, which no doubt is only sensible once one understands the need to distinguish between radiation and radioactive matter. With people who are more familiar with the field of nuclear physics such micro-meanings of concepts could well be used, but one should not be surprised to find lay ideas even among those!

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