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Pre-university students' conceptions regarding radiation and radioactivity in a medical context

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ABSTRACT

In this study, the conceptions of pre-university level secondary students with respect to radiation and radioactivity were investigated. A literature review determined what was already known about secondary school students' conceptions that differ from scientific theory, regarding radiation and radioactivity. Next, 12 Dutch students and their teachers were interviewed. Half of the already known student conceptions were confirmed in the interviews. The most persistent conception was students' inability to distinguish between irradiation and contamination. All newly discovered conceptions, such as students' idea that radiation can exist independently of the source of radiation, were discovered within a medical context. A remarkable finding was that students have full confidence in medical professionals, while at the same time they believe that all medical imaging techniques are dangerous. It can be concluded that curricular developments and changes in teaching contexts lead to changes in student conceptions concerning established topics. Knowledge of these conceptions and how to change them might be an important focus for teacher training, as teachers play a role in overcoming conceptions that do not correspond with prevailing scientific theories and, at the same time, may be a source of these conceptions.

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Introduction

An X-ray at the dentist, radiation therapy at the hospital, a malfunctioning nuclear power plant—in one way or another, nowadays nearly everyone is confronted with radiation and radioactivity. However, radiation and radioactivity are difficult to understand because we cannot feel them with our senses. We develop our own conceptions of radiation and reasons based on our experiences and the information that we receive from others, be they parents, the media, or peers (Lijnse et al., 1990). Probably because everyone is confronted with radiation and radioactivity and they thus play an important role in modern society, this has become a compulsory topics in physics education worldwide.

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To be able to teach the topic of radiation and radioactivity, teachers need to know not only the physics, but also the pedagogical difficulties of teaching about radiation and radioactivity (Hunt & Minstrell, 1996; Strike & Posner, 1985). It was only in the second half of the twentieth century that radiation and radioactivity became a topic in educational research.

The first educational research paper about radioactivity was published by Riesch and Westphal (1975). They studied how students adjusted their mental images of matter to incorporate the existence of ionising radiation. After the nuclear disaster at Chernobyl in 1986, radiation and radioactivity received more attention in educational research. Three prominent examples of investigations carried out in the aftermath of this disaster were: Lijnse et al. (1990) studied students' ideas about radioactivity as it is addressed in mass media; Boyes and Stanisstreet (1994) research covered children's conceptual knowledge of the sources and the perceived dangers of radiation and radioactivity; and Eijkelhof et al.'s (1990a) investigation of the influence of mass media on students' ideas about radiation and radioactivity. The overarching research question in this research was: 'What do students know, or think they know about radiation and radioactivity?'

The aim of the research presented here was to find out what conceptions students have about radiation and radioactivity. The focus of this article is on all student's beliefs and conceptions that differ from scientific theory. Our first step was to develop an overview of what is already known about the difficulties students have with respect to radiation and radioactivity. We researched student conceptions, conceptions that do not correspond with prevailing scientific theories, that have been found in research about radiation and radioactivity among upper level secondary school students. Our first research question thus was: '*What conceptions are upper-level secondary students known to have about radiation and radioactivity?*'

Students' conceptions are influenced by their experiences, just as research and education are influenced by society. The Chernobyl disaster is an example of the influence of society on research. As a result of Chernobyl, for decades public discussion about radiation and radioactivity centred around the possibilities of nuclear disasters (Kim, 2016). Educational research, likewise, focused on the same aspects of radiation and radioactivity (Boyes & Stanisstreet, 1994; Eijkelhof et al., 1990a; Lijnse et al., 1990).

Compared with other subjects, significantly less research has been conducted into conceptions regarding radiation and radioactivity (Pfundt & Duit, 1988). Only five of Duit's (2009) 550 articles about student conceptions referred to conceptions with regard to radiation or radioactivity. Moreover, following changes in society and in the research, high school physics curricula evolved accordingly. The first high school physics courses that included radiation and radioactivity as topics focused on the principles of radiation and radioactivity (Bower & Robinson, 1955; Dull et al., 1955). During the cold war, the focus in school education shifted towards the dangers of radiation and radioactivity (Hawkins & Phelps, 1975). In more recent years, the context in which radiation and radioactivity are taught in secondary schools has shifted further towards benign applications, for example, medical imaging (e.g. X-ray and CT scanning) and medical treatments (e.g. radiation therapy and positron therapy).

Little educational research has been done to investigate students' conceptions about radiation and radioactivity with regard to a medical context. None of the five publications about students' prior knowledge of radiation and radioactivity investigated the medical

context. As conceptions depend on the context (Lijnse, 1990; Mortimer & El-Hani, 2014), it is important to look into students' existing conceptions about radiation and radioactivity within the context in which radiation and radioactivity are taught, and this context has recently changed. For example, in the USA, the Next Generation Science Standards (Council, 2012; States, 2013), proposes the teaching of the principles of wave behaviour and wave interactions with matter in the context of medical imaging. In the UK, a significant proportion of the physics curriculum focuses on the medical, industrial and commercial use of these principles (Education, 2015). In the Netherlands radiation and radioactivity concepts are now taught in the context of medical applications (NiNa, 2006, 2010).

There are multiple views on the nature of student conceptions and how to deal with student conceptions, to achieve conceptual correctness (for example Hammer (1996), Mortimer (1995) and DiSessa and Sherin (1998)). The similarity between these views is that teachers need to know what existing student knowledge is because the development of knowledge is a process during which students assimilate new, scientific information into prior knowledge, which can cause hybrid conceptions or misconceptions (Vosniadou, 2019). For teaching radiation and radioactivity effectively, it is important to know which conceptions appeal most to students. The teacher then can anticipate potential conceptual problems and hybrid ideas (Duit & Treagust, 2003; Potvin, 2017).

To summarise, as most of the research into conceptions of radiation and radioactivity was conducted decades ago in a completely different society, the conceptions of students have likely changed. At the same time, the context in which radioactivity and radiation concepts are taught has changed from the dangers of atomic bombs and the risk of nuclear disaster, to benign applications of radiation, such as in medical applications. This is another reason why students' conceptions could have changed. For that reason, we also answered the following questions: 'What conceptions about radiation and radioactivity in a medical context do Dutch pre-university level secondary students (14–16 year-olds) have nowadays?' and 'What do teachers know about conceptions of upper-level secondary students about radiation and radioactivity?'

Method

The first research question was answered by means of a structured literature search. We used Web of Science, Scopus and ERIC for that purpose. Our search query was: (radiation OR radioactivity) AND (preconceptions OR misconceptions OR layman ideas OR children's ideas OR pupil ideas OR student knowledge OR student conceptions OR intuitive notions).

This resulted in 58 articles found in Scopus and 50 publications in ERIC. The Web of Science search resulted in 68 studies. Subsequently, these results were filtered using the following criteria: (1) the article focused on student conceptions, (2) the article had to be about research with upper level secondary school students, and (3) the subject of the article had to be radiation or radioactivity. A total of 20 articles matched the criteria and were analysed for our purpose, see the supplemental online materials for the complete list of this literature search.

Our second research question (*conceptions about radiation and radioactivity in a medical context*), and third research question (*teacher knowledge of student conceptions*

regarding radiation and radioactivity) was answered by means of semi-structured interviews with pre-university level students and their teachers. The physics teachers responded to an invitation to participate in our research. Their schools were located in various parts of the Netherlands, both in cities and in rural areas. In each school, two students were selected by their teacher (all students participated voluntarily) based on the following criteria:

- (i) The students had to be students at the pre-university level.
- (ii) The students had not yet received formal education on radiation or radioactivity.

Students' teachers were interviewed to tap their pedagogical knowledge on radiation and radioactivity: Which concepts are difficult for students to grasp and which conceptions do teachers observe among students? All participating teachers were qualified to teach radiation and radioactivity. The teachers' background varied; both university-trained teachers and teachers with a Higher Vocational Education background were interviewed, see [Table 1](#).

Instruments

Student interviews

Semi-structured interviews were used for answering the second research question, which allowed for follow-up questions to be asked. In this way, we could have a conversation with the participants and ask for elaboration and clarification of their responses. Interviews were always held with two students together. All interviews were held in Dutch, recorded and transcribed verbatim. See [Table 1](#) for detailed information about the interviewed students.

The interview questions (see the supplemental online materials) were inspired by the work of Eijkelhof (1990c), which enabled the comparison of the findings of our study with his findings nearly thirty years earlier. Precisely the same questions about X-ray

Table 1. Participants interviewed on student conceptions with regard to radiation and radioactivity in a medical context.

City	Teacher training background	Teacher experience in years	Student age	Students' average physics grades*	Student gender
Haarlem	University	10	15	6.5	M
			15	7.5	M
Schagen	Higher vocational degree	17	15	6	F
			16	6	M
Haarlemmermeer	Higher vocational degree	3	15	9	F
			16	9	M
Tilburg	University	32	14	7	F
			15	5	M
Nijmegen	University	19	15	7.5	F
			16	5	M
Gouda	University	18	14	9	F
			15	9	F

* The physics grades of the students are considered to be an indication of their overall achievement level in physics at the time of the interview (ranging between 1 and 10; a grade below 6 is considered to be unsatisfactory and 10 is the highest possible grade).

radiation were used in our interviews. The questions about basic radiation and radioactivity concepts were aligned with students' everyday experiences. A series of queries on medical treatments and imaging techniques such as MRI and proton radiation were added to the list of questions, as these other medical treatments had not yet been investigated before at the secondary school level. These questions were based on the work by Kaczmarek et al. (1987) and Mubeen et al. (2008), who studied medical students' conceptions of radiation and radioactivity.

The interview questions were categorised, as in the work of Eijkelhof, into five categories: basic concepts, X-rays, irradiation for cancer treatment, other medical imaging technics, and other sources of radiation. Each category included a number of basic questions and some follow-up questions, see the supplemental online materials.

Teacher interviews

The teacher interviews started with a short introduction about student conceptions and the question whether they knew of any conceptions not corresponding to prevailing scientific theory regarding the topic of radiation and radioactivity. This was followed by questions about the same topics as the ones covered by their students, but teachers were also asked about problems they encountered when teaching these topics, and about the issues they noticed when correcting student work. See [Table 1](#) for detailed information about the interviewed teachers.

Data analysis of the interviews

The student interview data were analyzed by means of content analysis of the transcribed protocols in Atlas.ti (Muhr, 2016). The first coding cycle was open: all non-scientific notions were coded. For example, 'I think that they use radioactive radiation' was coded as 'no distinction between radiation and the radiating particle'. In the second coding cycle, all quotes were grouped based on the student conceptions found in the literature, or in new categories that had emerged from the first coding cycle. In this cycle, the previous example was placed under the known conception: 'Radiation is the same as radiating particles'. During this second coding cycle, the context in which the conceptions had been found was noted. The coding of the teacher' interviews was done in a similar way.

Results

Student conceptions with respect to radiation and radioactivity

The results for our first research question: 'What conceptions are upper-level secondary students known to have about radiation and radioactivity?', are presented in [Table 2](#).

Many conceptions were found in only one or two publications. Only one conception deviation from prevailing scientific theory was found in almost every publication listed here: students do not make a distinction between contamination and irradiation (Boyes 1994; Cao & Dominguez Castineiras, 2016; Colclough et al., 2011; Lijnse et al., 1990; Nakiboğlu & Tekin, 2006; Neumann & Hopf, 2012; Plotz, 2016). This conception

Table 2. Student conceptions of upper level pre-university students regarding radiation and radioactivity from both the literature review and our interviews.

		Categorised by the source of the conception		
Student conceptions based on the inability of human senses to detect ionising radiation and radioactivity directly		References	Number participants mentioning the conception	
			Students (12)	Teachers (6)
1	Radiation is not natural.	2, 4, 5, 7, 9, 11	2	1
2	All electrical devices emit harmful radiation.	4, 7, 9	4	0
3	Radiation is emitted by living creatures and helps us to detect feelings.	4, 7	0	0
4	Light is different from radiation.	1, 4, 5, 7, 11	3	3
5	Radiation is responsible for many environmental problems.	1, 4, 6, 7	0	0
6	Radiation of natural sources is helpful, radiation of nuclear waste is harmful.	1, 9, 11	0	0
7	X-rays should be extracted from air in order to reduce radiation risk.	8	1	0
8	All medical imaging technologies and all medical treatments use harmful radiation.	New, from interviews	9	3
9	Radiation is seen as something independent of the source of radiation. Radiation exists, like any other particle.	New, from interviews	6	3
10	Radiation has a chemical source, being made during chemical processes and absorbed by chemical substances. Chemotherapy is an example of this.	New, from interviews	9	1
11	Ionising radiation is radiation emitted by ions	New, from interviews	2	0
12	There is no background radiation or if there is, its pollution or from nuclear accidents.	New, from interviews	0	3
13	The properties of α -, β -, or EM-radiation are the same.	New, from interviews	0	1
Student conceptions based on the stochastic nature of decay				
14	Temperature affects radioactivity. Decay rates of any radioactive substance decrease as temperature increases.	9	0	0
15	A cell cannot be alive as long as the half-life of potassium-40. This means that radiation cannot occur.	9	0	0
16	After one half-life, half of a radioactive sample disappears.	2, 8	3	0
17	Isotopes with long half-lives are more unstable.	2	0	0
18	Radiation is dangerous independent of the radiation dose.	1, 2, 6, 10, 11	5	1
19	Atoms cannot be changed from one element to another.	6	0	0
20	Once a material is radioactive, it is radioactive forever.	6	0	0
21	Radiation might accumulate in the human body.	8, 11	0	2
22	Radiation can kill instantly, just as in Hollywood movies.	New, from interviews	0	2
Student conceptions based on language difficulties				
23	Radiation is the same as radiating particles.	1, 4, 5, 7, 10	10	1
24	irradiation can lead to contamination.	1, 2, 3, 5, 6, 7, 8, 10	8	6
25	If an object is exposed to ionising radiation, it becomes radioactive.	1, 2, 3, 9, 10	0	0
	1 Boyes and Stanisstreet (1994)	4 Eijkelhof (1996)	8 Plotz (2016)	
	2 Cao and Dominguez Castineiras (2016)	5 Lijnse et al. (1990)	9 Sesen and Elif (2010)	
	3 Colclough et al. (2011)	6 Nakiboğlu and Tekin (2006)	10 Millar & Gill (1996)	
		7 Neumann and Hopf (2012)	11 Rego & Peralta (2006)	

suggests that you will become contaminated if you receive radioactive material by eating or breathing, but also as a result of irradiation.

A second common student' believe is about the nature of radiation. Ionising radiation is seen as something unnatural by a number of students. Several researchers have found that

students see ionising radiation as something man-made, an undesired result of industrial processes (Eijkelhof, 1990c; Neumann, 2012; Sesen & Elif, 2010). This may be linked to their idea that ionising radiation is responsible for other unintended processes, such as the greenhouse effect, the hole in the ozone layer, or environmental pollution.

Most studies found one or more conceptions related to the way students use language. Students describe radiation in exactly the same way as the source of the radiation. They do not make a distinction between the source of the radiation, the radioactive object, and the radiation produced by this object (Boyes, 1994; Eijkelhof, 1996; Lijnse et al., 1990; Neumann, 2012; Sesen, 2010). Moreover, several researchers found that in the minds of students, visible light is something completely different than radiation (Boyes, 1994; Neumann, 2012; Plotz, 2016).

Three studies mentioned that students see radiation and radioactivity always as something dangerous (Boyes, 1994; Cao, 2016; Nakiboğlu & Tekin, 2006). They seem not to distinguish between different kinds of radiation, for example, particle radiation, (e.g. α -radiation) and electromagnetic radiation (e.g. γ -radiation), nor do they seem to distinguish between gamma radiation and infrared radiation, radiation types which differ greatly in terms of energy density. Students seem not to differentiate in terms of the radiation dose, either. In their view, radiation is always dangerous independent of radiation period or radiation intensity.

Two studies mentioned conceptions related to half-life (Cao, 2016; Plotz, 2016). Some students do not grasp the concept of half-life, or just make something up, resulting in the believe that after two half-life times have elapsed, no radiation is produced anymore or that decaying matter has been converted completely into radiation.

Sources of conceptions with respect to radiation and radioactivity

The conceptions found in the literature, if categorised, the categorisation was based on physics principles such as the source of radiation, the mode of travel and the origin of radiation. These categorizations are based on where the student conceptions diverge from the scientific model. However, conceptions are mostly formed before students are taught formally, so a physics categorisation based on didactical difficulty is not logical. Therefore, we developed a categorisation based on the causes of the conceptions. In most studies an explanation for a conception was provided, which were used for our categorisation of student conceptions.

These cause-based categorizations of conceptions include three categories. The first category includes conceptions attributable to the fact that radiation is invisible (Prather & Harrington, 2001). The second category originates from the stochastic nature of radioactivity (Resnick, 1996). The last category arises due to differences between professional and everyday language (Neumann, 2012). These three categories will be clarified below.

Many conceptions are related to man's inability to sense radioactivity, or to detect ionising radiation. This prevents students from having direct experiences with radiation and radioactivity. They receive information about radiation mostly from non-scientific sources. The media warn about the dangers of radiation, for example, the dangers caused by the storage of radioactive material. However, the media are not clear about the exact nature of these dangers. This leads to multiple conceptions deviating from scientific theory, for example: 'radiation is not natural'. Students argue that if radiation is natural,

we would have had the senses to detect it (Boyes, 1997). Another conception caused by this lack of access by the senses is that ‘radiation is responsible for the greenhouse effect’. Being unable to detect radiation, students blame everything on this invisible phenomenon.

The second category of student conceptions originates from the stochastic nature of radioactivity: there is no detectable cause why atoms decay or do not decay. There is only a chance that a nucleus will decay within a certain period of time, being unaffected by physical quantities such as temperature or density. This independence of its surrounding is difficult to comprehend and leads to multiple conceptions, such as: ‘once a material is radioactive it is radioactive forever’ (Nakiboğlu & Tekin, 2006), or ‘a cell cannot be alive for as long as the half-life time of potassium-40. This means that radiation cannot occur’ (Sesen, 2010). Both conceptions are based on misinterpreting the concept of half-life, the time by which half of a sample of radioactive material will decay. A third conception caused by this stochastic behaviour is related to the half-life time: ‘after one half-life, half of the radioactive material is gone’. Many students have no idea that during decay, the atom changes into another kind of atom (Boyes, 1994).

The last cause of student conceptions is linguistic: the discrepancy between the professional use and the daily use of the same words. If teachers use the term radiation while teaching the topic of radioactivity and radiation, radiation is understood to mean ionising radiation: α -, β -, or γ -radiation. In contrast, outside of this specific topic, radiation or light is used if solar radiation (UV radiation, visible light and infrared radiation) is meant. This can lead to prejudices such as: ‘Light is different from radiation’ (Plotz, 2016). These language difficulties are related to the most common student conception deviation from prevailing scientific theory: ‘radiation is the same as radiating particles’. These students do not distinguish between the particles that radiate during decay and the radiation produced by these particles. This is strengthened by a phrase commonly used in Dutch and German, which could be translated as: ‘radioactive radiation’. Table 2 gives an overview of all conceptions found, categorised according to the three sources of conceptions mentioned above.

Known conceptions regarding radiation and radioactivity in a medical context

We did not find research in this literature search that focused on student conceptions in a medical context in secondary schools, with the exception of a small part of Eijkelhof’s PhD (1990c) research. Most articles found were mostly inspired by the Chernobyl (Lijnse et al., 1990) or Fukushima (Neumann, 2012; Neumann & Hopf, 2013) nuclear power plant disasters. As conceptions are dependent on the context (Lijnse et al., 1990; Mortimer & El-Hani, 2014) it is important to look at conceptions that arise within a medical context.

Conceptions related to medical applications of radiation and radioactivity were investigated to some extent with other types of students. Mubeen et al. (2008) studied medical students’ knowledge of ionising and non-ionising radiation, and Freudenberg and Beyer (2011) studied the perceptions of radiation risk held by medical students and non-radiologic physicians. This research revealed conceptions about X-ray radiation: that gamma rays are less hazardous than X-rays; X-rays stay for hours in the air in an X-ray department; and, after completing X-ray examinations, objects in the room emit radiation. Along with these conceptions, patients informed about, and treated with, radioactive medicine also showed a high level of distrust in radioactivity (Freudenberg & Beyer, 2011; Mubeen et al., 2008)

and are ill informed about the risk involved (Ricketts et al., 2013; Sin et al., 2013). However, none of these studies involved secondary school students.

Therefore, we looked into the differences in conceptions between secondary school students and medical students, as well as patients who have had experience with medical treatments (Freudenberg & Beyer, 2011; Mubeen et al., 2008). First, many of the conceptions of secondary school students were not found in research with medical students or patients. Moreover, only one of the conceptions found with medical students was already known from research outside the medical context. It is not clear whether medical students do not have the most common conceptions because of their higher levels of education, or that the conceptions were not found because the studies in which medical students were involved focused on conceptions related to medical applications.

Some of the conceptions found among medical students were not found among secondary school students. This does not necessarily mean that secondary school students do not have these conceptions. Not all medical applications of radiation and radioactivity were investigated in studies in secondary schools, and possibly students did not know that some medical applications use radiation and radioactivity. It is likely that, as students did not have experience with all medical applications of radiation and radioactivity, they had not developed their own knowledge of the application. It is possible that secondary students do not yet have any conceptions, but may very well develop these when confronted with these unknown applications of radiation and radioactivity.

Most prominent in research focusing on conceptions in a medical context was that by Eijkelhof (1990c). One of the applications used in that study was X-rays in hospitals. Getting an X-ray is a familiar context for both students in the 80's and students in our times. Where in Eijkelhof's research, students compared X-ray with photographs and with the properties of light, this comparison did not occur in our interviews. This may be caused by the changed way in which photographs are developed: today all photos are digital, resulting possibly in less knowledge about the principles involved. Even in the same context, student conceptions have changed over time due to technical developments which bring about changes in society.

Two conceptions mentioned in our interviews, the idea that all medical imaging techniques use harmful radiation and that radiation has a chemical source, were not found by Eijkelhof in the 80's. This could be a result of three social changes. First, there are more medical applications nowadays and they are used much more often. As a result, less attention is paid to X-rays specifically. Students encounter different techniques and the dangers of these techniques could be mixed up by students. Secondly, chemotherapy is nowadays a well-known cancer treatment in addition to radiation. Students may be confused by these two treatments and this could lead, in their minds, to a chemical basis of radiation. Finally, it should be noted that, compared to the 1980s, students have less overall knowledge of radiation and radioactivity in general, possibly because less attention is paid to radiation and radioactivity in the media.

Students' conceptions with regard to radiation and radioactivity in a medical context

To answer our second research question we conducted a number of semi-structured interviews with students and their teachers. Sixteen conceptions deviating from scientific

theory about radiation and radioactivity were found; see Table 2. Nine of these were confirmations of the conceptions that had been found in the literature; six of them were not mentioned in the literature. The three most prominent conceptions from these interviews will now be discussed in detail.

Most prominent during the interviews was the belief of students that all medical imaging technologies use harmful radiation. Students seemed to know that X-rays are harmful for the human body, but also believed that ultrasounds are malefic, even when they acknowledged that ultrasounds use sound waves to produce images. Their conceptions differed from the scientific view:

[ultrasound], for example during pregnancy, they watch sound waves in it and then create an image of it all. It is just a measuring device of frequency ... I think it's just quite expensive, too, because there's also gel involved, I think they use the gel because it's protective. I don't know that, but it could be. (student 1)

Most prominent in the literature and quite common in the interviews was the inability of students to distinguish between contamination and irradiation. Equally, students made no distinction between radiating particles and radiation itself. When asked about X-rays, students said things such as: 'I think, they use radioactive radiation for it' (student 2), or 'yes, radioactivity is released by using it' (student 3). In response to the question: 'Would you be allowed to visit patients who have just received irradiation', students answered: 'No, I think the hospital will only admit visitors if there is no risk of further contamination' (student 4). Furthermore, this inability of students to make a distinction between irradiation and contamination is the only conception that was acknowledged by all teachers.

The third conception repeatedly found was that students see radiation as something on its own. They do not make the necessary connection between the source of the radiation and radiation itself. We found that many students believe that all radiation is just like any other particle: a substance. All students had experience with X-rays themselves, at least as a result of photos taken at the dentist. When asked if the X-ray examination room at the hospital needs to be ventilated because of all the X-rays done during the day most student acknowledged this:

If the released radiation just keeps floating around in the room and reflects on all the walls, then after a day it will be completely full. And it does not decompose immediately, so it must be ventilated, otherwise the last person will get extra radiation immediately. (student 4)

Besides these prevalent conceptions, some conceptions were found only in a few interviews. First, students seem to have a mental image in which radiation and radioactivity are mainly chemical. They said things such as: 'The radiation is absorbed by chemicals in the air' (student 4), 'There is a lot of radiation in old chemical plants, like old power stations' (student 5) or 'Isn't chemotherapy the same as radiation?' (student 1). Second, students do not make a clear distinction between particle radiation and other types of radiation. One of the interview questions was: 'What is the place you have ever been with the highest level of radiation?'. The expectation was that students would answer with things like: near a nuclear power plant or in a hospital. However, one student responded with 'The place with most radiation I have ever been is the Saturn (a store selling computers, televisions, mobile phones)' (student 3). They see

radiation as something dangerous, not only ionising radiation, but also visible light and Wi-Fi. Third, most students did not know anything about the half-life time of radioactive substances. In the single interview in which a student mentioned half-life time, he thought that a radioactive substance would be completely gone after two half-life times. The known conception that 'radiation is not natural' was mentioned in a single interview. The explanation for this thought was: 'If radiation is natural, we would have had the senses to detect radiation' (student 6).

It is noteworthy that in contrast to earlier research (Freudenberg, 2011), more than half of the students showed a high level of trust in medical professionals: 'If it's okay with the doctor, it has to be safe' (student 6).

Most occurrences of conceptions were found when students were talking about everyday life, or in a context of X-ray radiation. In contexts with which students are less familiar, such as ultrasound, nuclear power plants, nuclear bombs, radiation therapy and MRI, fewer conceptions that do not correspond with prevailing scientific theories were found. A possible explanation could be that students have not developed conceptions linked to these contexts yet.

Teachers' views on student conceptions with regard to radiation and radioactivity

Teachers did not mention many conceptions, either based on the literature or on their own experience. Only two conceptions known from the research were mentioned more than twice in the interviews. All teachers knew about the inability of students to make a distinction between irradiation and contamination. About half of the teachers mentioned that students have one mental image for all types of radiation (the properties of α -, β -, or EM-radiation are the same). For example, 'Students find it difficult to comprehend that a stove also emits electromagnetic radiation and that ionising radiation contains the same photons with much more energy' (teacher 1). On top of that, some teachers do not have knowledge of how to achieve conceptual change. For example, one of the teachers said: 'Well, I just explain things and then basically they know how it is' (teacher 2) when asked what he does when he notices that there are problems regarding the difference between contamination and irradiation.

Although teachers did not mention many conceptions deviating from scientific theory, they could point out what problems students typically struggle with during their lessons (see Table 3). The problems they mentioned were mainly the struggle with new concepts and procedures. The problems mentioned included the introduction of many new physics quantities and their units: students have difficulty linking the units with the appropriate physics quantity, for example, linking Sievert to equivalent dose. Teachers also mentioned students' lack of procedural knowledge in terms of using the right mathematical procedures, which includes logarithmic calculations and linking activity to decay in $N(t)$ -diagrams.

Teachers also play another role with respect to student conceptions: they are a potential source of these alternative conceptions. During the interviews, almost all teachers spoke about radiation or even radioactive radiation when they actually meant ionising radiation. This is reflected in the loose way students speak about radiation and radioactivity. This could also be caused by the mass media speaking about radioactive radiation,

Table 3. Student problems based on the inability of the human senses to detect ionising radiation and radioactivity directly.

	Quotes	Number of teachers mentioning the difficulty
1 Relationship between activity and number of radioactive isotopes and the relationship between activity and the slope of a N,t-diagram	Activity, they have the feeling, that it's the number of particles that are still there, they don't realise it is caused by the change in the number of particles.	4
2 Half-value thickness causes many problems as this depends on both the properties of the radiation and the material.	They understand that the dust is twice as thick, but they also have to use the energy of the photon that comes out of it, and then they often have to interpolate the results, and then it gets bad.	3
3 Penetration depth versus half-value thickness. Students struggle with differentiating between these two quantities.	Half-value thickness and penetration depth, yes, they should look at it differently for each particle. They don't make that difference right away, no.	3
Student problems based on the stochastic nature of decay		
4 Assessing risks, students think radioactive decay is always dangerous.	They see it as dangerous, no risk assessment. And that in combination with radiation, because it's abstract.	1
5 Students have to work with logarithms, and find this difficult.	Insufficient mathematics skills to apply logarithms causes problems.	4
Student problems based on the complexity of the topic		
6 Many new quantities, mixing up all unknown quantities with which they do not have any hands on experience.	What I find very difficult for students is that there are so many extremely similar concepts.	1
7 Many new units, of which students have never heard before.	You have J/kg, Gy, Sv and with activity you have Bq while it's basically per second, yes they have a problem with that. There are even those that use Hz as unit.	4
8 Students have problems with the many mental steps they have to go through when working on assignments.	That's also because there are too many mental steps, but they're all very simple mental steps, but there are a lot of them.	2

for example: 'Your body is constantly exposed to small amounts of natural radioactive radiation', as is said on a website of a Dutch power company, hosting the biggest nuclear power station of the Netherlands (EPZ, 2020).

Conclusions

In this study, conceptions deviating from prevailing scientific theory of radiation and radioactivity held nowadays by pre-university level students were investigated. The conceptions found in a literature review were compared with those found in interviews. Some differences were to be expected, as a result of the fact that society, an important source of informal learning, has changed. In addition, the context in which radiation and radioactivity concepts are taught has changed. Both factors are known to influence the formation of conceptions.

In response to our first research question: '*What conceptions are upper-level secondary students known to have about radiation and radioactivity?*', we can conclude that the literature tells us that students do not make a distinction between contamination and irradiation, that they do not see differences between radiating particles and radiation itself, that students see all radiation as something dangerous and that radiation is not considered to be natural by students.

Most of students' conceptions are formed based on their experiences and the information they gather in the media. However, some conceptions are also caused by teachers. We found in our interviews examples of sloppy language use by teachers and students, which is also present in mainstream media. This could reinforce students' inability to distinguish between ionising radiation, visible light and particle radiation.

The results for our second and third research questions: '*What do teachers know about conceptions of upper-level secondary students about radiation and radioactivity?*' and '*What conceptions about radiation and radioactivity in a medical context do Dutch pre-university level secondary students (14–16 year-olds) have nowadays?*' are in line with and contribute to what was already known before our study. Many conceptions found in the literature were confirmed in our interviews with Dutch students and their teachers. Some new conceptions emerged, often related to the medical context in which they were found. The most apparent student conceptions that we observed were: students think that all medical imaging techniques use harmful radiation; radiation is seen by students as something that can exist independent of the source of the radiation; radiation is thought by students to have a chemical basis.

A striking finding is that students show great confidence in medical professionals, in contrast with the suspicious attitude found by Freudenberg and Beyer (2011). While students have faith in their doctors, at the same time, they think that all medical imaging techniques use harmful radiation, including ultrasound, even when they know that soundwaves are used in ultrasounds. It suggests that students have a split view of medical applications of radiation; Students do not possess detailed knowledge of many medical applications of radiation and radioactivity, and they possess even less knowledge of the risks involved. They have knowledge of the physics concepts that relate to medical applications and also have an idea of the risks involved with these medical applications, but they cannot establish a link between them. We found that students were not able to relate the risks of, for example, ultrasound to the physics concepts involved (reflection and soundwaves). This lack of knowledge and the inability to weigh different aspects, such as the risk of irradiation compared to the advantage of non-invasive medical treatment, lead to a different approach to school tasks than experts (Chi et al., 1981).

Of all the conceptions found, the independence of radiation from its source was the most frequently observed. In all contexts that we encountered in our interviews, such as X-rays, food irradiation, or everyday life, the same conception emerged: students think that radiation can exist independent of a source. They see radiation in a similar fashion as particles: if there is radiation, the radiation particles cannot just disappear, even in the case of X-ray or gamma radiation.

Another problem that has persisted despite societal changes is students' loose usage of physics concepts such as radiation, radioactivity and radioactive radiation. This points to troubles students have when thinking about the differences between radiating particles and radiation. Student conceptions have proven to be robust; the changes in society and the changes in contexts do not seem to interfere with the development of these conceptions. The only study about radiation and radioactivity in a medical context that was done before this one was the research by Eijkelhof (1990c). His interview questions about X-rays and everyday life were used in our study to investigate the changes in conceptions over a timespan of thirty years. In those thirty years, both the experiences of students and the context in which they are confronted with radiation and radioactivity have changed.

We found that students' conceptions with regard to X-rays and everyday life stayed the same, whereas their general knowledge with respect to nuclear waste and the Chernobyl accident has decreased.

When secondary school students were compared with medical students, it became clear that medical students have different conceptions. Part of the differences in conceptions could be linked to the medical students' higher level of education. Other differences in conceptions, for example, conceptions found only with medical students, can possibly be explained by secondary students' lack of experiences with medical procedures and therefore their not yet having developed their own conceptions.

Comparing our results with the results from Eijkelhof's research in the 80's shows that student conceptions related to X-rays have changed. This could be explained by the higher number of medical technologies commonly used and the frequent combination of radiation and chemotherapy in cancer treatment. Both could possibly lead to new and other confusions for students. The changes in society, combined with the changes in how media reports about radiation, could explain the changes in conceptions of secondary school students.

In general, most changes between students' conceptions found in literature and in interviews are related to changing contexts. The conceptions found in this study emerged mainly from everyday life discussions and in medical contexts. This is a shift from earlier research, in which many conceptions were developed in the context of the atomic bomb or nuclear disasters. This change in contexts may be a cause of the change in conceptions. Students are less often confronted with the dangers of radiation and radioactivity and have more experiences with medical applications of radiation.

Discussion

Several new student conceptions were detected in this research and most conceptions that were already known from the literature were confirmed. Our study also revealed that the teachers involved did not seem to know which conceptions live among their students. During the interviews, only one teacher mentioned any conceptions in addition to the most well-known, that students cannot distinguish between contamination and irradiation. Knowing which conceptions are present is essential for overcoming these conceptions that do not correspond with prevailing scientific theories, for example, by confronting students with the difference between their conceptions and expert concepts (Kendeou & O'Brien, 2014; McLure et al., 2020; Smith et al., 1994).

Teachers mentioned only a few misconceptions, but could pinpoint many problems linked to the many new concepts within the topic of radiation and radioactivity, and the more complex mathematical procedures required. It seems that teachers do not frame the problems students have with subject matter as known misconceptions (Leuchter et al., 2020).

In addition, teachers proved to have little knowledge of theories of conceptual change and of how to put these theories into practice (Smith et al., 1993), and (NEA, 1920, p. 49):

The teaching of the past has too frequently assumed that a principle may be readily grasped if only it be once stated in clear language and illustrated by a few examples, and that it may then be generally applied with comprehension and completeness.

As this study was of an exploratory nature, we think it is important to test our findings in representative samples. We recommend that students and teachers be interviewed (for studying student conceptions) in various countries, as they may have different conceptions because of differences between countries in the information provided in the mass media and differences in the learning contexts in those countries.

In order to obtain better insight into student conceptions in a medical context, we also recommend a study among medical students. It is possible that such students, because of their higher level of experience in the medical context have developed more and other conceptions. By studying these conceptions and by expanding our knowledge base about the conceptions students can have, it may be possible to better prevent the development of such conceptions.

We recommend that the available knowledge about student conceptions deviation from prevailing scientific theory should be utilised more. More attention should be paid in pre-service and in-service teacher training to potential conceptions that do not correspond with prevailing scientific theories just as to how to deal with those conceptions.

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