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Radiation and Rational Deliberation

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Abstract

There is uncertainty and disagreement about the question which preventive actions are rationally justified with regard to moderately elevated levels of nuclear radiation. This may have at least four causes: ignorance, insufficient information, inconclusiveness and indeterminability.

After the nuclear disaster with the Fukushima nuclear power plant the advice, given by some authorities, to leave Tokyo was largely based on the former two factors: ignorance and insufficient information. By contrast, the uncertainty and disagreement amongst experts about the size of the area to be evacuated was mainly caused by the latter two factors: inconclusiveness and indeterminability.

Inconclusiveness concerns the question whether moderately elevated radiation levels cause real and significant health risks that require drastic measures.

Indeterminability concerns the problem of rationally weighing disparate benefits and costs of the preventive measures, to wit, expected health benefits versus the costs and burdens of mass evacuation.

The International Commission on Radiological Protection (ICRP) recommends that no measures should be taken unless they produce a positive net benefit.

Exposure to moderately increased levels of radiation may increase the risk of fatal cancer in the future, while mass evacuation has burdensome and disruptive consequences for the society and for the persons who have to leave their residential and/or working area for a long time.

Ordering of mass evacuation seems rationally and ethically justified only if the expected future benefits outweigh the present and future burdens. Small or uncertain future health benefit may be outweighed by large costs and burdens of mass evacuation.

Because we have to take into consideration not only public but also individual costs and benefits, it is important to take into account the personal *absolute* increase in health risk of elevated radiation in addition to *relative* risk.

Unlike relative risk, absolute risk reveals the individual chance of getting a radiation-based disease. The increase in absolute risk – that is, the difference between the chances of getting the disease with and without the exposure to the increased level of radiation – is a useful measure to reveal the personal chance of health benefit from evacuation. This personal benefit must be balanced against the personal costs and burdens.

The key question is which levels of radiation absorption and health risks outweigh the burdens of mass evacuation. There seems consensus amongst experts about the justification of mass evacuation in cases of expected individual radiation absorption > 500 mSv over a year. Similarly, experts agree that expected extra radiation absorption < 10 mSv does not justify mass evacuation. But between these two extremes there is a wide range of 50-fold increasing radiation levels in which it is not clear whether the personal and public benefits from mass evacuation outweigh the personal and public costs. This may partly explain why experts and authorities gave conflicting advice about the radius of the area around the Fukushima nuclear power plant within which people had to be evacuated.

The uncertainty about the right thing to do with respect to a wide range of moderately elevated levels of radiation seems to be caused not only by inconclusiveness but also by indeterminability, that is, impossibility of determinately weighing disparate costs and benefits.

Introduction

When the earthquake and tsunami at the north-east coast of Japan had damaged the Fukushima Nuclear Power Plant, more than 100,000 people living within a 20-km radius of the plant were ordered to evacuate. Those within a 30-km radius were advised to stay indoors.

The U.S. Embassy in Japan recommended a larger evacuation zone for American citizens. All persons who lived within 80 kilometers of the plant were advised to leave the area.

Also Greenpeace concluded that the authorities had to re-evaluate the evacuation zone to better reflect radiation levels being found across the region.

On March 15^{th}, four days after the earthquake, elevated concentrations of nuclear radiation were measured in Tokyo, 240 km from Fukushima. The radiation levels were on average 15 times higher than normal. Several foreign governments advised their citizens and embassies to leave the city.

By contrast, the International Atomic Energy Agency declared that dose rates in Tokyo were not dangerous to human health and were far from levels which would require action.

How to declare the discrepancies between advices of authorities with respect to preventive measures that should be taken against the elevated radiation?

According to the International Commission on Radiological Protection (ICRP) preventive practices are not justified unless they produce a positive net benefit. In other words, preventive measures are justified only if the advantages outweigh the disadvantages. Evacuation is a burden that has to be weighed against the expected health damage caused by the elevated radiation. If the health risk is high, the health benefit from evacuation is large. In that case evacuation is the right decision. If, by contrast the increase in risk is small, the burden of mass evacuation may outweigh a limited or uncertain future health benefit. In that case evacuation is not justified according to the ICRP guidelines.

So the question of the right decision seems to be answerable if we know all relevant facts, to wit, the levels of radiation, the health risks related to these levels and the burdens and costs of evacuation.

However, the question is more complicated than that. The aim of this paper is to show that even if we completely know all facts on both sides of the balance, the weighing procedure may remain indeterminate. This indeterminability is reflected in, and may at least partly explain, the differences in advice given by experts who are equally competent and well-informed. The indeterminability is caused by the heterogeneity of the factors to be weighed against each other: the benefit of health protection versus the burden of mass evacuation. The difficulty of arriving at a determinate balance between these heterogeneous interests can be summarized by the following question: above which level of radiation and health risk is mass evacuation rationally justified?

The answer to this question is complicated by the fact that (at least over a large range of radiation exposures) there seems to be a linear dose-effect relationship between radiation and health risk: an *x* times higher radiation exposure causes an *x* times larger health risk. A gradually increasing radiation exposure causes a gradually increasing health risk, which slowly changes from insignificant to significant. This seems to mean that there is no clear-cut level of radiation exposure below which the risk is insignificant and above which the risk is significant. In the lowest range of radiation levels the risks are insignificant, and in the highest range they are significant, but in-between there is a wide range in which the levels are more or less significant, or neither very insignificant nor very significant. The absence of a clear-cut shift from insignificant to significant risk, together with the heterogeneity of the elements to be weighed, seems to cause indeterminability in the weighing of health risk against the burden of evacuation.

The title of this paper is 'Radiation and *rational deliberation*'.The following four factors may complicate a rational decision between alternative policies:

1. *Ignorance*
2. *Insufficient information*
3. *Inconclusiveness*
4. *Indeterminability*

Let us call them the 'four I's'.

Ignorance means lack of knowledge of the scientific facts, for instance, concerning the nature and level of health risk related to exposure to nuclear radiation.

Insufficient information means lack of information about the actual situation or state of affairs (for instance, about what exactly happened with the Fukushima nuclear power plant). Of course, there may be some overlap between the second and first 'I' in the sense that insufficient information may cause some kind of ignorance, but the ignorance meant under the first 'I' concerns lack of knowledge about the scientific facts rather than lack of knowledge due to lack of information.

Inconclusiveness means that there is not yet sufficient scientific evidence about the right answer to some *factual* questions, but that the right answer can, at least in principle, be found, in the near or distant future. Possible causes of inconclusiveness are, for instance, still incompletely developed science and/or the complexity of the relevant issue.

Indeterminability means that an unambiguous and definite or single right answer to the question what's the right thing to do, does not exist, even in principle. In other words, even if all relevant data are completely known, there is no right, or single right, or single rational, answer.

Unlike inconclusiveness, indeterminability is not caused by human insufficiencies such as gaps in scientific or other knowledge, but by the fundamental *impossibility to determinately weigh* the alternatives for choice (for instance, the alternative policies). As we will see, this is caused by the heterogeneity and incommensurability of the advantages and disadvantages connected with the competing alternatives.[1]

In sum, inconclusiveness concerns lack of evidence about particular *facts*. Indeterminability, by contrast, concerns the problem of *weighing* incommensurable values.[2]

To further illustrate the difference between inconclusiveness and indeterminability, I will give an example.

There is large disagreement amongst scientists about the number of long-term cancer deaths caused by the nuclear disaster in Chernobyl.

In a report by the World Health Organization the total number of long-term fatal cancers caused by the accident with the Chernobyl nuclear power plant in 1986 is estimated at 4000 people.[3] According to Greenpeace the total number of long-term cancer deaths must be estimated much higher, namely at about 100,000.[4]

Given this considerable difference in estimates, the right answer to the question how many cancer deaths have been caused, and will still be caused, by the Chernobyl disaster is still unknown. For several reasons it is difficult to determine the right number of deaths attributable to the radiation exposure after the accident.[5] Still this is *not* an example of indeterminability. It is an example of inconclusiveness. Of course there must be a single right answer to the question how many deaths have been caused, and will be caused, by the disaster, even though we do not know it yet (and even though we will perhaps never know it).

Suppose, we estimate the real number at, say, 10,000. Then there are not more than three possibilities with respect to the correctness or incorrectness of this number: the estimated number is larger than, smaller than, or equally large as the real number.

These three possibilities concern the so-called 'trichotomy thesis': with respect to *quantitative* comparisons between *Q1* and *Q2* there are only three possibilities:

1. *Q1* is *larger* than *Q2*

2. *Q1* is *smaller* than *Q2*
3. *Q1* is *equally large* as *Q2*

By contrast, with respect to *qualitative* comparisons of two valuable alternatives *A* and *B* (for instance two rival policies, each of which has its own advantage and/or disadvantage) the trichotomy thesis need not be true. There may be *four* instead of three possibilities:

1. *A* is *better* than *B*
2. *A* is *worse* than *B*
3. *A* is *equally good* as *B*
4. *A* is neither definitely better than, nor definitely worse than, nor (roughly) equally good as, *B*.[6]

If we want to determine whether in the case of a particular exposure to nuclear radiation it is better to evacuate than not to evacuate, we have to make a *qualitative*, or evaluative, rather than *quantitative* comparison. It concerns a *weighing* procedure: we have to weigh the possible health damage against the burden of mass evacuation.

However, how is it possible to determinately weigh two incommensurable things, like health damage and burden of mass evacuation? Here the problem of 'indeterminability' or 'incomplete comparability' may apply.[7]

We will see that the uncertainties and disagreements about the extent of the area to be evacuated and about whether or not to leave Tokyo can be explained by one or more of the four 'I's' (Ignorance, Insufficient information, Inconclusiveness and Indeterminability).

As will be shown, the advice to leave Tokyo was based on ignorance (insufficient acquaintance with scientific facts) and insufficient information. By contrast, the discrepancy between expert judgments on the necessity of mass evacuation is largely caused by inconclusiveness and indeterminability.

Inconclusiveness concerns the question whether a moderately elevated radiation level causes a real and significant increase in health risk, while indeterminability concerns the difficulty or impossibility of weighing a moderately increased health risk against the burden of mass evacuation.

After a brief discussion of the first three factors this essay will focus on the problem of the fourth factor, 'indeterminability – a phenomenon that is fundamentally different from ignorance, insufficient information and inconclusiveness.

Ignorance

As said already, on March 15^{th}, four days after the earthquake, significantly elevated concentrations of nuclear radiation were measured in Tokyo. The radiation levels were on average 15 times higher than normal. This induced some foreign governments to advise their citizens and embassies to leave the city.

Embassies issued warnings to their nationals to leave Tokyo or Japan. Britain advised its nationals living in Tokyo and areas north of the Japanese capital to consider leaving, while the Russian Foreign Ministry evacuated the families of diplomats working at the Russian Embassy in Tokyo. Australia and Germany also advised their citizens in Japan to consider leaving Tokyo and earthquake-affected areas. France sent extra aeroplanes to Japan to evacuate its citizens from Tokyo. Many foreigners in Tokyo stopped their work and their planned activities. For instance, Dutch artists were organising expositions in Japan but they decided to abandon them and returned to the Netherlands.

Germany's Foreign Ministry advised its citizens in the capital region to either leave the country or move to the Osaka area. Serbia and Croatia advised their citizens to leave Japan, while Croatia said it was moving its embassy from Tokyo to Osaka because of the nuclear crisis.

Several countries, amongst others my home country, ordered their journalists to leave Japan because of the radiation danger.

Let us examine whether these reactions and measures were rational. Were they based on good reasons? Were the risks in Japan larger than, for instance, in Libya, a country from which journalists were *not* called back?

There is much misunderstanding about the risks of radiation. Many people believe that *any* level of ionizing radiation is dangerous.

This fear is unfounded. First, we are all exposed to natural background radiation. Ionizing radiation reaches us from outer space and it comes from radionuclides present in rocks, buildings, air, and even our own bodies. Second, increased nuclear radiation does not necessarily, even not usually, cause cancer but may cause a more or less increased *risk* of cancer. The relevant question is how *much* the risk increases. Thus, it is important to know the *size* of the risk of future health damage. What is the risk of fatal cancer caused by the 15 times elevated radiation levels measured in Tokyo?

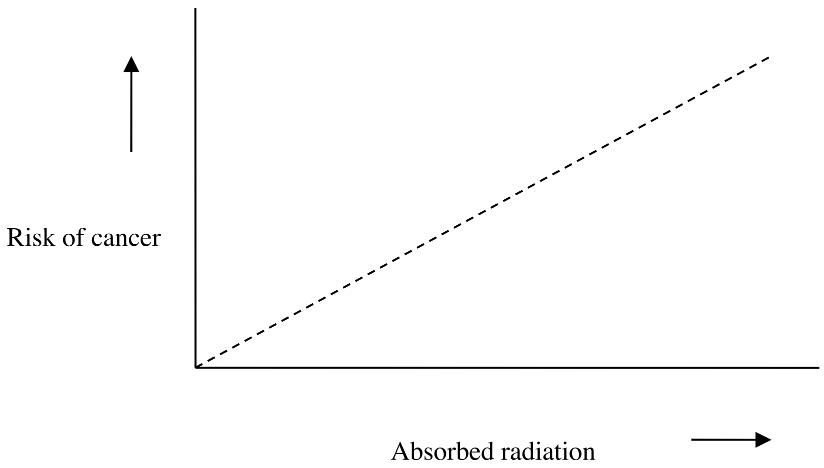
Amounts of radiation absorbed by the body are expressed in so-called Sieverts.

1 Sievert (Sv) = 1000 mSv (millisievert) = 1,000,000 μSv (microsievert)

There is a linear relationship between amount of radiation absorbed and the size of the increased risk.

Figure 1

Linear dose-effect relation between absorbed radiation and risk of cancer



At the time of the disaster with the Fukushima nuclear power plant I heard on the radio a reporter asking to a radiation expert: "Is there a health risk in Tokyo, yes or no? One cannot be a little pregnant: one is pregnant or not pregnant."

Apparently the reporter believed that health risk is analogous to pregnancy in the sense that it is either present or absent. This is a widespread misunderstanding. Unlike pregnancy, which is either present or absent, there may be a small, moderate or large health risk, as is shown by the above graph.

The dose-effect relationship means that fifteen times increased radiation levels, as measured in Tokyo, increase radiation-induced risk of fatal cancer in the future by 15 times. This sounds dramatic and seems a good reason to leave Tokyo. But we will see that this is not the case.

Normal background radiation

We have to put elevated radiation levels, such as those measured in Tokyo, into perspective. The increased radiation levels measured in Tokyo on March 15th can be estimated to amount to about 7 mSv if the exposure to these levels would continue during one year.

This can be calculated as follows:

On March 15th the maximally measured level of radiation was 0.809 microsievert per hour. That is 24 x 365 x 0.809 = 7087 microsievert per year. That is about **7 mSv** a year.

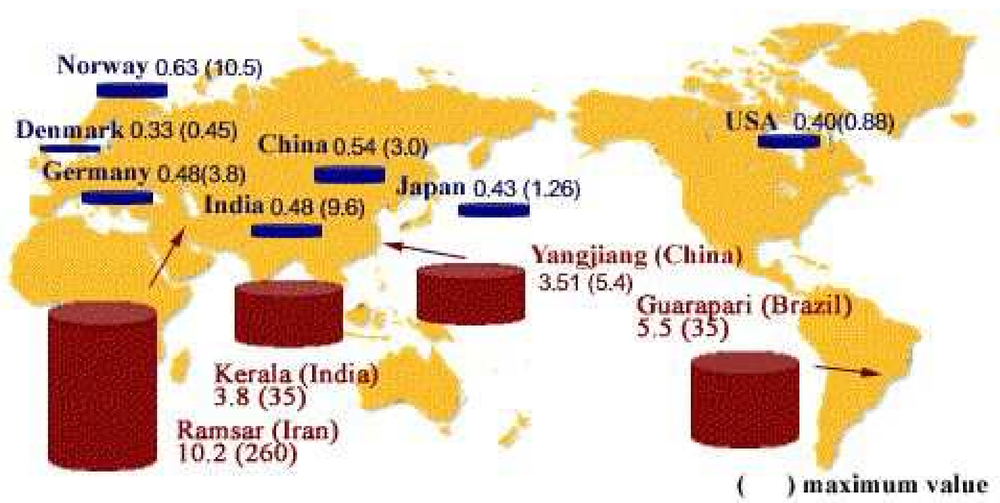
If we compare this with the figures mentioned in *table 1* and *figure 2* below, it seems there was no rational reason to leave Tokyo in a hurry.

Table 1. Some radiation exposures that are usually regarded as unproblematic

Normal background radiation in some parts of the world (e.g. in some parts of Iran, Brazil and India)	**> 10 mSv/yr**
Radiation absorbed by airline crew flying the New York/Tokyo polar route	**9 mSv/yr**
Radiation absorbed during chest CT scan	**10 mSv**

Normal background radiation is on average about 2 mSv per year. But the *range* of background radiation is very large, varying from less than 0.5 mSv/yr to more than 10 mSv/yr, and at some places even sometimes more than 100 mSv/yr! However, there is no evidence of increased cancers or other health problems arising from these high natural levels.[8]

Figure 2. Natural background radiation (mSv/yr) in different parts of the world



Source: S. M. Javad Mortazavi (Biology Division, Kyoto University of Education), *High Background Radiation Areas of Ramsar, Iran*.

Figure adapted from Health Research Foundation, Kyoto.

From the data of *table 1* and *figure 2* we can conclude there was no rational reason to leave Tokyo. A chest CT-scan (10 mSv) or living in Ramsar (10 mSv) in Iran or being a pilot who regularly flies the New York/Tokyo polar route (9 mSv) causes more absorption of radiation than one year exposure to the 15 times increased radiation levels measured on March 15th in Tokyo (7 mSv).

Table 1 and *figure 2* suffice to show that leaving Tokyo in a hurry because of the relevant increased levels of radiation is simply irrational. The figures would have been able to reassure people who considered to leave Tokyo. It was not surprising that the International Atomic Energy Agency declared that dose rates in Tokyo were not dangerous to human health and were far from levels which would require action.

Relative and absolute risk

It is important to make a distinction between relative and absolute health risk. On population level relative risk is relevant, while on individual level absolute risk is more pertinent.

Mass evacuation of large numbers of people who must leave their residential and/or working area for a long time, have serious and disruptive consequences. That is why mass evacuation is rationally and ethically justified only if the personal and public benefits outweigh the personal and public burdens.

This is different from preventive measures to which the so-called 'prevention paradox' applies: many preventive measures, which may be very beneficial for the society as a whole, may be of minor significance for each separate individual. For instance, wearing seat belts by all car drivers may prevent a substantial number of fatal car accidents on population level, while the individual driver has usually no personal benefit in the sense that the driver prevents a fatal car accident that would have occurred without wearing a seat belt. In this case the insignificant personal benefit is no convincing reason to regard the measure unjustified, because the burden of wearing a seat belt is very small. By contrast, if the relevant measure is burdensome for each individual, as is the case in mass evacuation, a small individual benefit from the preventive action may be outweighed by the large individual burden caused by it.

Let us consider an example. The damage to the Fukushima nuclear plant has multiply increased the radioactive radiation level. This enlarges the risk of radiation-related diseases. The estimated life-time risk of getting a radiation-related fatal cancer is 0.005% (5 per 100,000 persons) if one is exposed to 1 mSv extra radiation in addition to normal background radiation.[9] Suppose that the exposure to radiation has increased 10-fold and that this results in a 10-fold increase in radiation-related fatal cancer. In terms of *relative* risk ('10-fold' larger risk) this seems a significant increase. However, in terms of *absolute* risk the picture is less serious. In absolute terms the risk has become 0.05% instead of 0.005% (*table 2*). This is an increase in absolute risk of 0.045%. This is not very dramatic, especially if we realize that the 'normal' life-time risk of fatal cancer due to other factors than radiation is already 25%. The 10-fold increased risk related to the 10-fold increased exposure to radiation entails that the life-time risk of fatal cancer increases from 25% to 25.05%. This implies an increase of the number of cancer deaths per 10,000 persons from 2500 to 2505, an increase by 5 persons.

The difference in absolute risk of fatal cancer between exposure and non-exposure to the relevant elevated levels is a measure of individual benefit from evacuation: it indicates the chance of individual benefit in terms of preventing fatal cancer in the future which would have occurred without evacuation. In the example under consideration the difference in absolute risk is 0.045%, which is simultaneously the chance of personal benefit (*table 2*). In other words, if 10,000 persons are evacuated, 45 persons will prevent a fatal cancer in the future which would have occurred otherwise (without evacuation). This means that 9,955 of 10,000 evacuees do not experience advantage, only the disadvantages of evacuation. The chance of personal benefit increases linearly with increasing exposure to radiation.

Table 2. Relative and absolute risk of fatal cancer related to a 10-fold elevated exposure to radiation (in addition to normal background radiation) from 1 to 10 mSv and the chance of personal benefit from evacuation.

Initial absolute risk (without increased radiation)	RELATIVE RISK (caused by increased radiation)	NEW ABSOLUTE RISK	INCREASE OF ABSOLUTE RISK	CHANCE OF PERSONAL BENEFIT FROM EVACUATION
0.005%	10	0.05%	0.05% -0.005% = 0.045%	**0.045%**

Insufficient information

Rational decision making is improved by adequate information. However, adequate information cannot always take away all uncertainties, for two reasons:

1. There may be inconclusiveness even amongst experts (for instance, there is still always uncertainty about deleterious effects of moderate levels of radiation).
2. There may be rational indeterminability (for instance, related to the question of which level of increased risk outweighs the burdens of mass evacuation).

Inconclusiveness

It is still unclear whether low doses of radiation increase the risk of cancer. The prevailing assumption is that any dose of radiation, no matter how small, involves a possibility of risk to human health (the non-threshold hypothesis). However there is no scientific evidence of risk at doses below about 50 millisievert in a short time or about 100 millisievert per year.

Higher accumulated doses of radiation might produce cancer which would only be observed several - up to twenty - years after the radiation exposure. This delay makes it impossible to say with any certainty which of many possible agents were the cause of a particular cancer. About a quarter of people die from cancers, not related to radiation.

Standards and regulations

Radiation protection standards are based on the assumption that the risk is directly proportional to the dose, even at the lowest levels, though there is no evidence of risk at low levels. As said already, this assumption is called the 'linear no-threshold hypothesis'.

One of the key points of the recommendations by the International Commission on Radiological Protection (ICRP) is the *justification* of preventive measures:

・ No practice should be adopted unless its introduction produces a *positive net benefit*.

When is mass evacuation justified?

The Japanese government ordered more than 100,000 people living within a 20-km radius of the damaged Fukushima Nuclear Power Plant to evacuate. Those within a 30-km radius were advised to stay indoors.

The U.S. Embassy in Japan recommended a larger evacuation zone for American citizens. All persons who lived within 80 kilometers of the plant were advised to leave the area.

Also Greenpeace concluded that the authorities had to re-evaluate the evacuation zone to better reflect radiation levels being found across the region.

How to declare the discrepancies between advices of authorities with respect to preventive measures that should be taken against the elevated radiation?

As mentioned above, according to the ICRP preventive practices are not justified unless they produce a positive net benefit. In other words, preventive measures are justified only if the advantages outweigh the disadvantages. Evacuation is a burden that has to be weighed against the expected health damage caused by the elevated radiation. If the health risk is high, the health benefit from evacuation is large. In that case evacuation is the right decision. If, by contrast the increase in risk is small, the burden of mass evacuation may outweigh a limited or uncertain future health benefit. In that case evacuation is not justified according to the ICRP guidelines.

So the question of the right decision seems to be answerable if we know all relevant facts, to wit, the levels of radiation, the health risks related to these levels and the burdens and costs of evacuation.

However, the question is more complicated than that.

Indeterminability

The answer to this question is complicated by the fact that (at least over a large range of radiation exposure) there is a linear dose-effect relationship between radiation exposure and health risk: an x times higher radiation exposure causes an x times larger health risk. As we saw already, a gradually increasing radiation exposure causes a gradually increasing health risk, which slowly changes from insignificant to significant. This means that there is no clear-cut level of radiation exposure below which the risk is insignificant and above which the risk is significant. In the lowest range of radiation levels the risks are insignificant, and in the highest range they are significant, but in-between there is a wide range in which the levels are more or less significant, or neither very insignificant nor very significant. The absence of a clear-cut shift from insignificant to significant risk, together with the heterogeneity of the elements to be weighed, causes the indeterminability in the weighing of health risk against the burden of evacuation.

The zone that should be evacuated is determined by a balance between the costs and burdens of massive evacuation *versus* the costs and burdens of the expected health damage if evacuation would not take place.

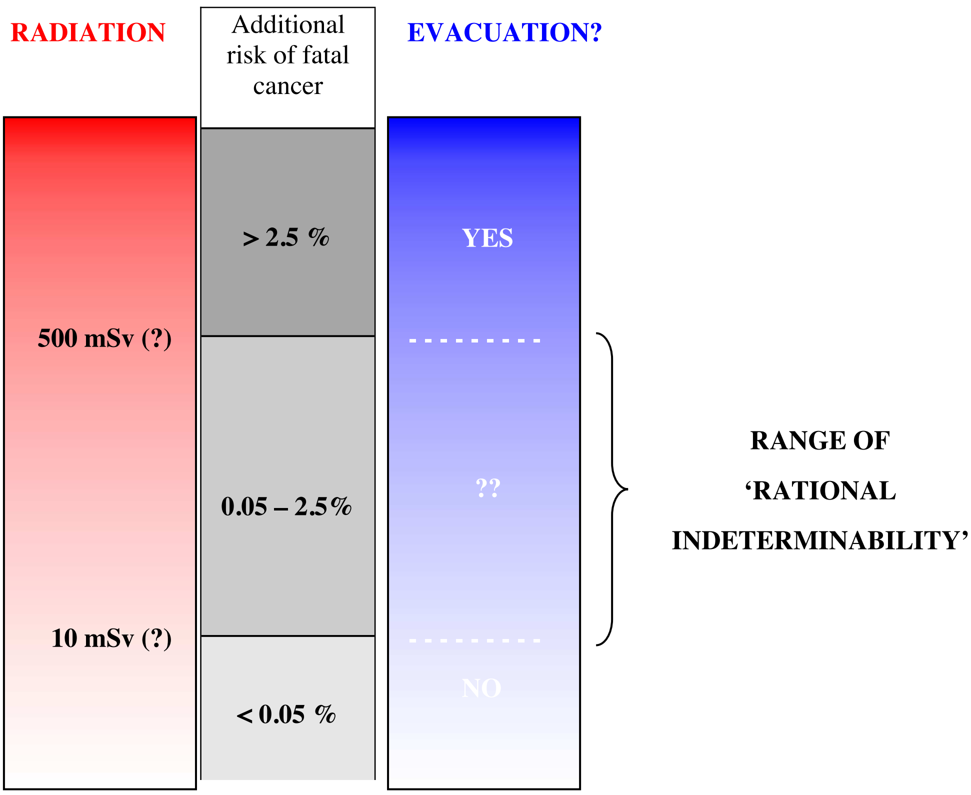
The key question is 'Which level of health risk is equivalent to the burden of mass evacuation?' If we know the answer to this question, we know whether a particular health risk surpasses the 'equivalence-level' so that mass evacuation is justified. But how can this equivalence-level be determined? Given the contradictory instructions mentioned above, different experts and authorities apparently arrive at different equivalence-levels. This may be the consequence of indeterminability rather than inconclusiveness.

The central problem of rational indeterminability is the absence of a determinate level of equivalence between incommensurable variables (benefits, burdens, costs). Suppose decision P (e.g. the decision to evacuate) yields a particular amount x of advantage A_1 (e.g. prevention of health damage), while decision Q (e.g. the decision not to evacuate) yields a particular amount y of advantage A_2 (e.g. avoiding the burdens of evacuation). The question whether option P outweighs option Q depends on the answer to the question which amount of A_1 is *equivalent to* the actual amount of A_2. If the amount of A_1 is larger than this 'equivalence amount', then P has more weight than Q.

However, the problem is that the question of equivalence may have no determinate answer because of the incommensurability[10] of the benefits and burdens. Without an answer to the question of the level of equivalence we do not know above which level of radiation it becomes rationally and ethically justified to order mass evacuation. In that case it remains indeterminate – at least over a wide range of radiation levels – whether a particular radiation level justifies mass evacuation.

Incommensurability and the resulting absence of a level of equivalence do not always prevent complete comparability of the alternatives and a completely justified decision. In the relevant issue, very high levels of radiation do, while very low levels do not, justify mass evacuation. But between very high and very low radiation levels there is a 'wide range of indeterminability' in which there is no determinate answer to the question of the right thing to do, because of the absence of a level of equivalence between incommensurable values, interests and burdens (see *figure 3* below). In the range of indeterminability the question 'How much risk justifies the burden of massive evacuation?' cannot be determinately answered. This means that, even if we exactly know the risk people run in the stricken areas, the right thing to do may remain rationally indeterminable.

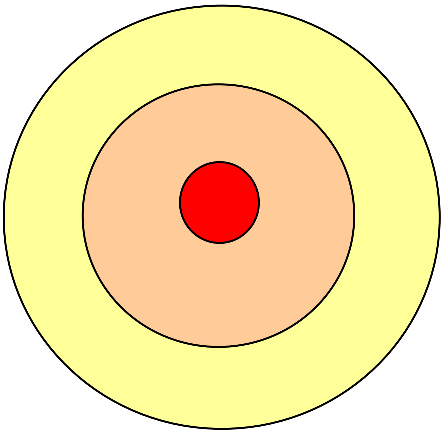
Figure 3. Which radiation-absorption levels (in a year?) justify mass evacuation?



In the zone of indeterminability it may be useful to leave it to personal decisions whether or not to move out of the relevant area (as the Japanese authority did in an area with a radius between 20 and 30 km from Fukushima). Here it is a question not so much of expertise but rather of weighing, which can be done in more than one rational and reasonable way, precisely because reason 'underdetermines' the choice. That is why equally rational, skilful and well-informed persons assign significantly different weights. This also explains why even different experts arrive at significantly different conclusions[11] and give contradictory advice.

The range of 'rational indeterminability' is reflected in the uncertainty about the question whether in the intermediate zone around the source of elevated radiation (the orange zone in *figure 4* below) mass evacuation has to be advised.

Figure 4



Extra radiation absorption a year: *

> 500 mSv: mass evacuation (?)

10-500 mSv: ??

< 10 mSv: no mass evacuation

* Expected cumulative radiation in addition to normal background radiation

Conclusions

This essay is to a large extent a theoretical exercise. However, the topic concerns practical reasoning, that is, rational deliberation about what we should do. That is why the theoretical conclusions and practical consequences largely coincide.

The difficulty to take justified decisions with regard to health risks related to elevated radiation levels may have different causes. The uncertainty about the right thing to do is not always the consequence of insufficient information or inconclusiveness. It may be caused by indeterminability, which means that a (single) right and determinate answer does simply not exist, even if all relevant scientific and other facts are completely known. This indeterminability is caused by the impossibility of determinately weighing incommensurable values, interests and burdens.

This is not to deny the importance of adequate public information about the actual state of affairs and the need of reliable scientific knowledge about the short- and long-term health effects of the relevant elevated radiation levels. Education and transparent public information may prevent that citizens become unnecessarily terrified and may promote insight in which measures are rational or irrational.

But even then, it may remain indeterminate whether the expected benefits from a particular action will outweigh the burdens. In those cases citizens themselves or politics will, after adequate information about the facts, have to make a decision, after having deliberated about the advantages and disadvantages of the measures to be taken.

Notes

[1] Two values are incommensurable if and only if they have different dimensions that cannot be reduced to one dimension so that their amounts cannot be measured and compared on a common cardinal scale of units of value. See Joseph Raz, who argues that in cases of incommensurable alternatives reason 'underdetermines' the choice. See Raz, *The Morality of Freedom* (Oxford: Oxford University Press, 1986), chapter 13.

[2] Although inconclusiveness and indeterminability are distinct phenomena, they may lead to similar decision problems (see, for instance, Isaac Levi, *Hard Choices. Decision making under unresolved conflict*. Cambridge University Press, 1999). The word 'indeterminability' is not mentioned in the *Oxford English Dictionary*, but I prefer this term to 'indeterminacy' because the latter is often identified with 'vagueness' or 'impreciseness', which is a different phenomenon.

[3] World Health Organization (2005) *Chernobyl: the true scale of the accident*.
http://www.who.int/mediacentre/news/releases/2005/pr38/en/

[4] Greenpeace (2006), *The Chernobyl Catastrophe: Consequences on Human Health*. The report can be downloaded at:
http://www.greenpeace.org/international/Global/international/planet-2/report/2006/4/chernobylhealthreport.pdf

[5] For instance, because of the following two reasons it is difficult to determine the right number of deaths. First, the number of people who have died and will die from cancer caused by the Chernobyl disaster is a tiny fraction of normal cancer deaths (the normal life-time risk of dying from cancer by other causes than radiation is already about 25%). This makes a population-based epidemiological study of the effects of radiation very difficult. Second, the result of a calculation of the expected radiation effects depends on what theory is adopted for the effects of very low radiation doses. Usually, the so-called non-threshold theory (that is, there is no threshold of radiation below which there is no health risk) is adopted, but this theory is not universally accepted.

[6] Ruth Chang calls this fourth value relation ‘parity’. [‘The Possibility of Parity’, *Ethics* 112 (2002): 659-688; and ‘Introduction’ in Ruth Chang (ed.) *Incommensurability, Incomparability and practical Reason* (Cambridge, Mass.: Harvard University Press, 1997)]

[7] For an extensive and thorough discussion of the possible problems of incommensurability for rational comparability see Ruth Chang (ed.) *Incommensurability, Incomparability and practical Reason* (Cambridge, Mass.: Harvard University Press, 1997), to which 13 leading theorists have contributed.

[8] World Nuclear Association [2011], *Radiation and Life*

[9] The estimated risk of fatal cancer is 5 of every 100 persons exposed to a dose of 1000 mSv (World Nuclear Association [2011], *Radiation and Life*). Assuming a linear non-threshold dose-effect relationship this means that 1 extra mSv causes an additional fatal cancer risk of 0.005%.

[10] For the definition of incommensurability, see footnote 1.

[11] For instance, Wade Allison who is a nuclear and medical physicist at the University of Oxford and the author of *Radiation and Reason* (2009), argues that “a responsible danger level based on current science would be 100 mSv per month, with a lifelong limit of 5,000 mSv, not 1 mSv per year [as is normally taken as limit]”.

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