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□ Scientific method is inherently self-correcting. When different hypotheses are proposed, their study would result in the rejection of the invalid ones. If the study of a competing hypothesis is prevented because of the faith in an unverified one, scientific progress is stalled. This has happened in the study of low dose radiation. Though radiation hormesis was hypothesized to reduce cancers in 1980, it could not be studied in humans because of the faith in the unverified linear no-threshold model hypothesis, likely resulting in over 15 million preventable cancer deaths worldwide during the past two decades, since evidence has accumulated supporting the validity of the phenomenon of radiation hormesis. Since our society has been guided by scientific advisory committees that ostensibly follow the scientific method, the long duration of such large casualties is indicative of systemic deficiencies in the infrastructure that has evolved in our society for the application of science. Some of these deficiencies have been identified in a few elements of the scientific infrastructure, and remedial steps suggested. Identifying and correcting such deficiencies may prevent similar tolls in the future.

Key terms: LNT Model, Radiation Hormesis, Scientific Method, Scientific Infrastructure

INTRODUCTION

The health effects of low dose radiation (LDR) have been the subject of vigorous debate for many decades, with a considerable disagreement in the scientific community even on the question of whether LDR is beneficial or harmful to human health (Little *et al.*, 2009; Tubiana *et al.*, 2009). The prevailing view recommended consistently by most international and national scientific advisory bodies since the 1950s is the linear no-threshold (LNT) extrapolation model hypothesis for estimating the cancer risk from LDR for radiation safety purposes (Calabrese, 2009). The absence of a threshold dose for carcinogenicity has led to concerns about even the smallest amount of radiation exposure, resulting in radiation safety regulations that require radiation doses to be kept "as low as reasonably achievable" (ALARA) (Hendee and Edwards, 1986). A contrary view to the LNT model is that of radiation hormesis whereby LDR stimulates bodily defenses resulting in better health including reduced cancers (Feinendegen, 2005). While considerable number of human and animal studies have shown the invalidity of the LNT model and the valid-

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ity of radiation hormesis (Luckey, 1991; Cohen, 2002), results from the analysis of atomic bomb survivor data, which are generally considered to be the most important data for estimating radiation health effects, have been used to justify the continuing use of the LNT model (NRC, 2006) and for the LDR carcinogenic concerns (Hall and Brenner, 2008). Recent analysis of the latest update to the atomic bomb survivor data has shown that the observed shape of dose-response curve for cancer mortality cannot be explained even qualitatively with the LNT extrapolation hypothesis but may be consistent with the radiation hormesis hypothesis (Doss, 2013b), implying there is no longer any strong evidence supporting the continued use of the LNT model. In addition, evidence and justification for radiation hormesis have become stronger in the past decade (Liu, 2003; Sakai, 2006; Liu, 2007; Redpath and Elmore, 2007; Luckey, 2008; Rithidech and Scott, 2008; Scott, 2008; Cuttler and Pollycove, 2009; Scott, 2011; Doss, 2012b; Doss, 2013b; Doss, 2013a; Feinendegen *et al.*, 2013) indicating radiation hormesis may be a valid phenomenon, and implying that the incidence of cancer could have been reduced in the 1980s by studying and applying radiation hormesis when it was proposed (Luckey, 1980). However, the radiation hormesis hypothesis could not be studied in humans in the 1980s prospectively because of the acceptance of the unverified LNT model hypothesis, the resulting ALARA principle, and the ensuing carcinogenic concerns regarding LDR. This has likely resulted in over 15 million preventable cancer deaths worldwide during the past two decades, in view of the current annual global cancer death toll of 7.6 million (Jemal *et al.*, 2011), and assuming ~10% reduction in cancer mortality may have been achieved from the use of radiation hormesis (Doss, 2013b). Since scientific progress requires the study of proposed hypotheses to determine their validity, the inability to study the radiation hormesis hypothesis prospectively in humans because of the faith in the unverified LNT model hypothesis appears to have derailed the scientific method. Considering that we have been guided in our use of radiation by the recommendations of various advisory bodies that ostensibly follow the scientific method, the large casualties and the prolonged duration over which they have occurred may be symptomatic of systemic deficiencies in the infrastructure of our society that has evolved for the application of science. The purpose of this article is to examine the reasons behind the dominance of the LNT model hypothesis and the resulting barriers to the study of the alternative hypothesis of radiation hormesis, in order to identify some of these deficiencies and to recommend possible changes to correct them and prevent similar tolls in the future.

HEALTH EFFECTS OF LOW DOSE RADIATION

How LNT model hypothesis became accepted for estimating cancer risk from LDR in the 1950s

The history of the adoption of the LNT extrapolation model for radiation safety in the 1950s has been chronicled in a recent publication (Calabrese, 2009). Among the factors that drove the move towards the LNT model in the 1950s were genetic concerns based on the discovery of radiation-induced mutations in drosophila melanogaster (Muller, 1927) and the reported linear dependence of these mutations as a function of radiation dose for high doses (Oliver, 1930). Another reason justifying the move towards the LNT model was the concern of increased cancers from LDR based on the observed linear dose dependence of leukemias in atomic bomb survivors for high doses of radiation (Lewis, 1957). Though there was little data at low doses, linearity at low doses was claimed raising carcinogenic concerns about LDR, and the conclusion was strongly supported by an accompanying editorial in a leading science journal lending validity to the concept of linearity at low doses (Dus, 1957; Calabrese, 2009). A third reason for the support of the LNT model in the 1950s was the pacifist campaign in progress at the time for the prevention of atmospheric testing of atomic weapons (Jaworowski, 2010). Thus, the LNT model became established in the 1950s, not because of scientific evidence showing harm from LDR, but for other reasons, though advocated by leading scientists and scientific advisory bodies. A historical overview of radiation protection policies has stated that actions taken by the advisory bodies of reducing the recommended radiation dose limits in the 1950s were to address public concerns, and not based on any observed harm from LDR (Sinclair, 1981).

Inability to study LDR prospectively in humans resulted in large uncertainties in LDR health effects

In spite of the lack of supportive evidence for the adoption of the LNT model in the 1950s as described above, most international and national scientific advisory bodies have since then consistently reaffirmed the use of the LNT model hypothesis for estimating the cancer risk from LDR (NRC, 1972; NRC, 1990; ICRP, 1992; NRC, 2006; ICRP, 2007). A contrary view to the LNT model is the hypothesis known as radiation hormesis according to which LDR stimulates bodily defenses resulting in better health including reduced cancers (Luckey, 1980; Luckey, 1991; Feinendegen, 2005). However, the radiation hormesis hypothesis could not be studied prospectively in humans when it was proposed in 1980 (Luckey, 1980), because of the LDR carcinogenic concerns based on the unverified LNT model hypothesis. Though a considerable number of observational studies (e.g. epidemiological and case-control studies) have been performed using population groups already exposed to LDR, such studies are inferior in comparison to prospective studies (e.g. randomized controlled trials) (Barton, 2000), and the conclusions from the observational studies, being subject to many confounding factors, have not been definitive. In addition, the detection of hormesis requires the study of dose response at low doses with sufficient statistical power, and most studies of dose response do not satisfy this criterion (Calabrese, 1994). Hence, in spite of considerable time and resources committed to the study of LDR health effects with observational studies during the past several decades, there is no agreement in the scientific community regarding the health effects of LDR, and they are still being debated (Little *et al.*, 2009; Tubiana *et al.*, 2009). There is even disagreement on the question of whether LDR is beneficial or harmful to human health. Two recent contemporary reports by advisory committees came to opposite conclusions regarding the use of the LNT model and the carcinogenicity of LDR (Tubiana, 2005; NRC, 2006). A recent workshop reviewing the results of epidemiological studies could not come to a definitive conclusion about LDR cancer risk in spite of evaluating studies lasting for many decades (Hall *et al.*, 2009), again indicating the need for high quality prospective studies to determine the health effects of LDR in humans.

Recent publications have invalidated the LNT model and supported the radiation hormesis model

The unreasonableness of a linear extrapolation of biological effects of high dose radiation (HDR) to lower doses becomes clear when one considers the qualitatively different cellular responses to high and low doses of radiation (Ding *et al.*, 2005; Yang *et al.*, 2006; Chaudhry *et al.*, 2012). LNT model bases its concerns regarding LDR on the initial damage to DNA from the LDR (Hall and Giaccia, 2006), and ignoring the resulting adaptive protection. When such adaptive protection (Feinendegen *et al.*, 2013) is taken into consideration, there would ultimately be less overall DNA damage from the LDR (Koana and Tsujimura, 2010; Osipov *et al.*, 2013). LDR and HDR have also been observed to have opposite effects on the immune system, with LDR enhancing it and HDR suppressing it (Liu, 2007). Since the immune system plays a major role in keeping occult cancers in check (Koebel *et al.*, 2007), this again suggests that extrapolation of carcinogenic effects of HDR to low doses may not be justified (Doss, 2012b). In fact, LDR has been shown to be effective for treatment of cancer in an adjuvant setting in animal models (Wu *et al.*, 2008) and in humans (Sakamoto, 2004), and has been proposed for the prevention and treatment of cancers (Cuttler and Pollycove, 2003; Farooque *et al.*, 2011; Doss, 2013a). In a study of second cancers in radiation therapy patients, tissues that were subjected to ~20 cGy had less second cancers per kg of tissue in comparison to the tissues not subjected to any radiation (Tubiana *et al.*, 2011), lending further support to the idea of the cancer preventive effect of LDR. Recent analysis of human epidemiological data has shown the cancer preventive effect of LDR in atomic bomb survivors and in the apartment residents in Taiwan who were exposed to radiation from contaminated building materials (Doss, 2013b). Thus, data and evidence published since the time of the opposing advisory committee reports (Tubiana, 2005; NRC, 2006) have overwhelmingly supported and validated the radiation hormesis model.

How many cancer deaths could have been prevented if we had studied radiation hormesis in the 1980s?

If we assume ~10% reduction in cancer mortality may be achieved from the use of radiation hormesis (as a conservative value based on the observed reduction in cancers due to LDR in various studies), and using the 7.6 million annual global cancer death toll (Jemal *et al.*, 2011), over 15 million cancer deaths may have been prevented worldwide in the past two decades from the use of radiation hormesis (Doss, 2013b). This estimate of preventable cancer deaths could very well be an underestimate, since a systematic study of radiation hormesis may have lead to the development of irradiation protocols that provide better cancer preventive effect than that assumed.

Reason for the large number of preventable casualties over a prolonged period

The long period over which these large number of preventable cancer deaths have likely occurred from not utilizing radiation hormesis (and are likely continuing to occur at the rate of ~2000 per day worldwide) indicates there has been a failure in adhering to the scientific method, since the self-correcting nature of scientific method would have corrected our approach to LDR health effects from the study of the competing hypotheses in a relatively short time, led to the recognition of radiation hormesis as a valid hypothesis, and avoided the long-term casualties of preventable cancer deaths from not utilizing radiation hormesis. Since we have been guided in the use of radiation by international and national scientific advisory bodies during this period, and such advisory bodies ostensibly follow the scientific method, these long-term preventable casualties indicate the presence of systemic deficiencies in our present societal infrastructure for the application of science. Identifying these deficiencies and correcting them may help avoid such large and prolonged preventable casualties in the future.

SYSTEMIC DEFICIENCIES IN THE SCIENTIFIC INFRASTRUCTURE

The scientific infrastructure of our society in matters relating to the health effects of radiation includes (1) international and national advisory bodies that provide the scientific consensus recommendations, (2) peer-reviewed publications by scientists that are utilized by the advisory bodies for formulating the recommendations, and (3) popular media that disseminate the scientific findings in peer-reviewed publications and the advisory body recommendations to the public. Some of the deficiencies of these elements of the infrastructure that have contributed to the deviation from the scientific method and the large human toll will be discussed now.

Scientific Advisory Bodies:

At the top of the hierarchy of the scientific infrastructure in the field of LDR health effects are the international and national scientific advisory bodies that provide guidance in the safe use of radiation. Their advisory reports are highly regarded in the scientific community and are routinely used by researchers for LDR cancer risk estimates. Their reports provide guidance to governments in establishing radiation safety regulations and policies, and also influence public perception of LDR health effects. Some of the deficiencies in the operation of the advisory bodies are:

1. Acceptance of an unverifiable hypothesis as a justification for recommending actions

Though the LNT model was adopted by scientific advisory bodies for guiding radiation safety in the 1950s, the LNT model hypothesis, as it relates to doses approaching zero, does not satisfy a basic requirement of a valid scientific hypothesis, which is that it result in verifiable predictions. If we have verifiable predictions from a hypothesis, we can perform experimental measurements to test the hypothesis, and accept it or reject it based on the agreement or disagreement of the measurements with the predictions, thus advancing our knowledge. Since all measurements have errors and uncertainties, in order to have a verifiable prediction from a hypothesis, the consequences of the action relevant to the hypothesis, e.g. cancers following exposure to LDR, need to be significantly different from the consequences of no action, i.e. cancers in the absence of radiation, taking into account the errors and uncertainties in the measurements. LNT model would be valid as a scientific hypothesis for doses approaching zero if the measurement error or the observed variation in cancer rates were exactly zero so that the infinitesimal increase in cancers predicted from an infinitesimal dose of radiation could be measured reliably. Cancer rates are known to be highly variable from place to place, and from year to year, and so the errors and uncertainties in its measurement are certainly considerably more than zero (Doss, 2012a). Thus, the LNT model hypothesis would not lead to a verifiable prediction for doses approaching zero, and so it is not a valid scientific hypothesis. However, it has been recommended for use by most scientific advisory bodies.

2. Using an unverified hypothesis to forbid testing of an alternative hypothesis

When the radiation hormesis concept was proposed in 1980 as an alternative hypothesis for LDR effects (Luckey, 1980), since the prevalent LNT extrapolation model was a hypothesis and not a validated theory, it was incumbent upon the advisory bodies to encourage the study of radiation hormesis hypothesis to determine its validity, because of the likely large impact on human health if it turned out to be valid, and also because scientific method requires study of proposed hypotheses to determine their validity. However, the advisory committees used LNT model as if it were a confirmed theory in recommending radiation safety policies such as ALARA, which effectively prevented testing of the alternative radiation hormesis hypothesis in the 1980s in humans prospectively when it was proposed. This may have resulted in over 15 million preventable cancer deaths worldwide in the past two decades as described earlier. In addition, LDR adaptive protection has shown promise for the reduction of neurodegenerative diseases (Doss, 2013c) for which presently there are no methods of prevention or cure. The study and validation of radiation hormesis hypothesis in the 1980s would have reduced the fear of LDR and facilitated human studies of its application for reducing neurodegenerative diseases in 1999 when LDR animal studies showed promise (Kojima *et al.*, 1999).

Thus, the recommendations from the scientific advisory bodies based on the LNT model hypothesis and the resulting regulations have effectively derailed the scientific method by increasing fear of LDR and forbidding the study of the alternative radiation hormesis hypothesis, likely stalling progress in preventing cancer and neurodegenerative diseases.

3. Lack of vigilance monitoring data contradicting the hypothesis used for recommendations given

When advisory bodies provide recommendations based on a hypothesis, and such recommendations are used widely for guiding government and public actions, it is incumbent upon the advisory bodies to be vigilant to observe if any new data or publications provide evidence against the hypothesis used, since such evidence may negate the validity of the advice given. Whereas many peer-reviewed publications have claimed evidence for carcinogenicity of LDR and support for the LNT model in human studies, closer inspection of the data has shown a reduction of cancers from LDR or deviation of dose-response from linearity indicative of the presence of radiation hormesis (Miller *et al.*, 1989; Cohen, 1995; Howe, 1995; Luckey, 1999; Cohen, 2002; Sponsler and Cameron, 2005). Though some of the individual studies may not have the statistical power to make a definitive conclusion about the reduction of cancer at low doses, the repeated observation of such reduction at low doses is indicative of the possible validity of the phenomenon, justifying reconsideration of the LNT model and examining the validity of the radiation hormesis hypothesis. The advisory bodies have ignored such data in continuing to advocate the LNT model. Animal studies have shown clearly the presence of adaptive protection from LDR (Luckey, 1991), but such evidence has been dismissed by the advisory bodies (NRC, 2006). The advisory bodies have also ignored the large accumulating evidence for the beneficial effects of LDR in reducing the impact of non-cancer diseases in animal models (Takehara *et al.*, 1995; Kojima *et al.*, 1999; Takahashi *et al.*, 2000) as well as in some human studies (Yamaoka and Komoto, 1996; Yamaoka *et al.*, 2004).

4. Providing recommendations which have no measurable benefit

Most advisory bodies have consistently endorsed the use of the LNT model for estimating the risk of cancer from LDR, and taking actions based on the estimated risk. Since cancer incidence is affected significantly by a multitude of modifiable risk factors like exercise (Willer, 2003) and diet (Johnson, 2004), it would not be possible to measure reliably any LNT model-based predicted increased risk of cancer from a very small increase in radiation exposure, because of the confounding effects of the various modifiable risk factors. Thus, the effect of LDR on cancer risk would not be measurable for low doses. This would be analogous to not being able to measure the carcinogenic effect of not engaging in physical exercise for a few days. Whereas long-term physical inactivity is associated with increased risk of cancer for many types of cancers (Courneya and Friedenreich, 2010), the effect of a few days of physical inactivity would not be detectable in cancer outcome studies. Hence, there is indeed no panic reaction if one is not able to exercise for a few days. In a similar manner, there is no need for a recommendation of urgent evacuation of the public by the advisory bodies if there is a likelihood of a slight increase in the radiation dose to the public, since the resulting increase in cancers predicted using the LNT model would not be measurable. In view of this, the benefit of reduced cancers from avoiding the slight increase in radiation exposure by evacuation would also not be measurable, whereas the cost of such evacuation (or cost for prolonging any evacuation already completed) can be significant, both in economic and human health toll, making such recommendations unwise, and unworthy of consideration.

5. Having a narrow focus on a single harmful agent as the cause of excess cancers

Though the ultimate aim of the advisory bodies in the field of radiation health effects is to improve human health, their singular focus on radiation as the sole cause of increased cancers has prevented them from making simple recommendations that they could have given to improve the health of populations already exposed to radiation, as for example the atomic bomb survivors. It is well known that healthy changes in diet and exercise can result in a measureable decrease in cancer risk (Anand *et al.*, 2008). For example, if the advisory bodies had stressed the importance of regular exercise in reducing cancers among the atomic bomb survivors, and the government had provided education, encouragement and support for regular exercise, there would have been reduced cancer mortality among the survivors (Doss, 2012b). Similarly, if the advisory bodies had recognized that the effect of exposure to LDR is similar to that of not exercising for a few days, and had advised the governments to be not concerned about LDR exposure in ending the urgent evacuations after the damaged nuclear reactors were brought under control, much of the prolonged evacuations and the disruption of normal life and the related large economic toll and psychological casualties (Bromet, 2012; Saji, 2013) could have been avoided in Chernobyl and Fukushima. Instead, the advisory bodies recommendations, singularly focused on radiation as the sole cause of excess cancers, have led to increased psychological stress in already irradiated population groups, e.g. atomic bomb survivors (Ohta *et al.*, 2000), and the populations exposed to LDR in Chernobyl and Fukushima (Bromet, 2012; Saji, 2013).

In summary, the recommendations of the advisory bodies resulting from not following the scientific method have led to an unjustified fear of LDR, prevented study of LDR health effects in humans, and many deficiencies in their operations have also caused substantial casualties. Since peer-reviewed publications have provided the key evidence used in formulating the recommendations of the advisory bodies, deficiencies in the current system of peer-reviewed publications will be discussed now.

Peer-reviewed publications:

Peer-reviewed publications provide a crucial part of the knowledge base to the scientific advisory committees in formulating their policies. Peer-reviewed publications are also generally considered as sources of credible information by scientists and the general public. For topics in which there is widespread agreement in the scientific community, peer-reviewed publications indeed perform very well as repositories of validated knowledge. When contentious issues are involved however, the current system of peer-reviewed publications has a major deficiency.

Discredited conclusions of peer-reviewed publications continue to influence scientists

Scientific method requires the study of different hypotheses in order to identify the hypothesis most likely to be valid. The fact that there is a large disagreement in the scientific community on a certain topic implies the hypotheses that have been proposed and studied are contradictory to each other, with considerable data and evidence available in peer-reviewed publications to support both the opposing hypotheses. Such ambiguities in the data and evidence exist because of possible errors and uncertainties in the measurements, errors in methods of analysis and interpretation, etc. Of course, in due course of time, only one correct answer to the contentious question would ultimately emerge. This implies that approximately half the publications on any contentious issue (assuming the scientific opinion is equally divided between the two sides) would ultimately prove to have been faulty. However, there is presently no facility for identifying publications that have lost their credibility because of errors or because of faulty analysis or interpretation, even after these have been identified in subsequent publications. The erroneous publications continue to be quoted in newer publications long after their conclusions have been invalidated. Thus, peer-reviewed publications, in their present form, do not serve well as repositories of validated knowledge on contentious topics, as a significant part of the published literature would provide support for the wrong hypothesis when dealing with a contentious topic. Because of this weakness in the current system, a significant number of scientists would accept the wrong hypothesis regarding a contentious topic by referring to published literature long after there is evidence to the contrary, slowing down the progress of science, since the progress of science requires the rejection of invalid hypotheses.

For example, the 15-country study of radiation workers has claimed increased risk of cancer in radiation workers who were exposed to low levels of radiation (Cardis *et al.*, 2005; Cardis *et al.*, 2007). This conclusion was influenced greatly by the data from the Canadian workers, and according to the authors, removal of the Canadian data would result in changing the conclusion of the study to no increased risk of cancer from LDR (Cardis *et al.*, 2005). In June 2011, Canadian Nuclear Safety Commission (CNSC) completed a re-analysis of the Canadian worker data and reported finding problems with the data (CNSC, 2011). Their report has stated that there is no evidence for increased risk of cancer in the Canadian radiation workers, and that CNSC is withdrawing the Canadian data from use pending further investigation (CNSC, 2011). With the Canadian data removed, the conclusion of the 15-country study would be annulled, and the study would no longer conclude that there is an increased risk of cancer from LDR. However, even two years after the release of the CNSC report, there has been no retraction of the conclusion of the 15-country study, and the study continues to be cited as evidence for increased cancer risk from LDR (Albert, 2013; Hung and Hwang, 2013; Smith *et al.*, 2013).

Another example is the atomic bomb survivor study (Ozasa *et al.*, 2012). The conclusion of the atomic bomb survivor study, as presented in the abstract, is that the shape of dose response for cancer mortality among the survivors is linear, with no threshold, apparently validating the current use of the LNT model (Ozasa *et al.*, 2012). However, the text in their own paper says the dose-response curve in the 0-2 Gy region has a significant deviation from linearity (Ozasa *et al.*, 2012). A re-analysis of the published data has shown that these data are more consistent with the radiation hormesis hypothesis than with the LNT model (Doss, 2012a; Doss, 2013b). Another conclusion of the atomic bomb survivor study (Ozasa *et al.*, 2012) that zero dose is the best estimate of dose threshold may also not be justified as it appears to be based on faulty analysis, since the linear functional form for dose-response they used in the dose-threshold analysis was too restrictive as it did not encompass the full range of the observed data. An analysis using a more general functional form has resulted in a conclusion that the presence of a dose threshold cannot be excluded (Doss *et al.*, 2012; Doss, 2013b). However, older, outdated atomic bomb survivor data (which had poorer statistics and did not have sufficient statistical power to show the deviation from linearity) continue to be quoted as providing support for the LDR cancer risks (Mathews *et al.*, 2013) or the LNT model (Nayar *et al.*, 2013) in recent publications.

In summary, peer-reviewed publications do provide a good source of reliable information on topics where there is broad agreement in the scientific community. For issues that are contentious, peer-reviewed publications do not necessarily present reliable information since a substantial fraction of the publications could have invalidated information or outdated data which support the wrong hypothesis. Since there is presently no facility for tagging publications with a reliability index, many scientists continue to use the discredited or outdated information in peer-reviewed publications, slowing down the resolution of contentious issues by prolonging the belief in and use of the wrong hypotheses, thus impeding scientific progress.

Peer-reviewed publications do influence the public opinion on scientific topics such as the health effects of LDR. However, most of the public do not obtain scientific information from peer-reviewed publications directly, but from coverage of the publications in popular media. Thus, popular media play a very important role in the scientific infrastructure, since they transmit the scientific information from peer-reviewed publications to the ultimate intended beneficiaries, the public. The deficiencies in the operation of popular media in disseminating scientific knowledge from peer-reviewed publications to the public will be discussed now.

Popular media:

Lopsided publicity to sensational side of contentious issues by popular media

Most peer-reviewed publications do not receive any publicity in popular media. However, when the conclusions of the publications would result in sensational headlines, even if they may be based on faulty analysis or interpretation of data and provide support to the wrong hypothesis in contentious topics, they tend to receive considerable amount of media coverage, since the media tend to prefer such stories, and the reporters for the popular media generally would not have the background or knowledge in the field to critically analyze the publications to identify the faulty analysis or interpretation. For example, publications that raised concerns regarding the increased cancers from CT scans (Brenner and Hall, 2007) received considerable amount of publicity in popular media (The Associated Press, 2007). On the other hand, publications that refuted such claims (Scott *et al.*, 2008) did not get any publicity. Such lopsided coverage by media tends to give a misleading impression on the contentious topics to the readers. The media coverage on the subject of radiation-induced cancers since the 1950s has heavily skewed the public opinion away from the known facts regarding LDR effects on cancer. The resulting fear of LDR among the public has been a major hurdle and has prevented the study of radiation hormesis in humans, stalling scientific progress.

Since many scientists not familiar with the literature on LDR health effects would also get their information on the topic from popular media, their opinions regarding LDR are also affected by such media coverage. The lopsided publicity to publications supporting the LNT model hypothesis in popular media has had a devastating effect on a timely resolution of this contentious issue in the scientific community, as the popular media reach much larger numbers of scientists and the public as compared to peer-reviewed publications. This issue of lopsided publicity appears to be a problem in other areas of science also, as for example indicated by the recent article entitled “When bad science makes good headlines: Bt maize and regulatory bans” (Romeis *et al.*, 2013).

In summary, the lopsided coverage of LDR health effects in popular media have contributed to derailing of the scientific method, both by skewing public opinion resulting in fear of LDR preventing study of radiation hormesis hypothesis, and also by influencing the opinions of scientists in favor of the discredited LNT model hypothesis and impeding progress in the resolution of this contentious issue.

CORRECTING DEFICIENCIES IN THE SCIENTIFIC INFRASTRUCTURE

Based on the above analysis, some steps can be taken to overcome the noted deficiencies in the scientific infrastructure. Advisory bodies should be required to consider only verifiable hypotheses as basis for tentative actions, i.e., the errors and uncertainties in measurements should be accounted for in proposing any hypotheses for consideration. Recommendations should only be made when the recommendations would result in measurable improvements. Also, unverified hypotheses should not be utilized for universal recommendations or actions, but should be tested in limited areas or regions, and when the validity of the hypotheses are confirmed from the measurements, their application should be expanded to larger areas. Unverified hypotheses should not be used to prevent testing of competing hypotheses. The advisory bodies should recognize the possibility that their tentative support for a particular hypothesis may not be justified, and be vigilant in monitoring new data and publications for evidence to the contrary. The advisory bodies should also be required to consider the overall health of the public which should be their ultimate goal, and not be narrowly focused on the harmful effects of particular agents only. The improvements to public health from the recommendations of the advisory bodies should be measured and quantified to evaluate the performance of the advisory bodies.

Authors of peer-reviewed publications should be encouraged or should be required to submit retractions to their articles if their conclusions have been invalidated with the advancement of knowledge. A system of rating publications for the validity of their results and conclusions should be established, so that readers may take the ratings into consideration when contemplating using the results and conclusions from the publications. For major topics for which there are competing opinions in the scientific community, an online database of data, arguments, and counter-arguments should be maintained which reflects the current state of knowledge, and independent groups of scientists from different backgrounds should be asked to make impartial evaluations of the accumulating evidence frequently to arrive at tentative conclusions on the contentious topics.

An independent professional organization should be formed to monitor publicity in popular media for peer-reviewed publications, and if there is lopsided coverage of publications on one side of a contentious topic, balancing information should be provided in the same or equivalent media.

Taking these steps would help our society in adhering to the scientific method and in reaching a timely resolution of any contentious issues based on data and evidence.

CONCLUSIONS

Scientific method is indeed very powerful because of its inherent self-correcting nature. Though our society has been guided in the area of LDR health effects by scientific advisory bodies, the deficiencies in the scientific infrastructure of our society have derailed the scientific method by disabling its self-correcting feature, resulting in substantial casualties over a prolonged period of time. Some deficiencies have been identified in the operation of the scientific infrastructure and suggestions have been made for correcting them. A thorough analysis would need to be conducted by a few appropriately constituted study groups to review these, identify other deficiencies in the scientific infrastructure, and generate remedial recommendations. Major changes are clearly needed in the societal scientific infrastructure for ensuring and optimizing benefits to the society from the application of science.

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