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THE FISHERMAN'S CARDS: HOW TO ADDRESS PAST AND FUTURE RADIATION EXPOSURES IN CLINICAL DECISION-MAKING

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Abstract

This educational piece describes how to address patients' past – and future potential – radiation exposures when making an imaging decision “now.” The BEIR committee has endorsed a linear no-threshold model to explain the relationship between radiation exposure and cancer risk. This model implies that past – and future potential – exposures should *not* impact current decisions. We present an analogy which deconstructs these counterintuitive conclusions and facilitates translation of key radiation-risk principles to practice.

Introduction

In recent years, there has been a strong impetus to implement dose-capturing technologies that enable patients' cumulative radiation doses from imaging to be tracked over a lifetime [1–4]. At the patient level, how should this newly available information be used? Based primarily upon the health outcomes of Japanese atomic bomb survivors, the U.S. Biological Effects of Ionizing Radiation (BEIR) committee has endorsed a linear no-threshold (LNT) model to explain the relationship between low levels of radiation exposure and cancer risk [5]. While translation of the LNT model to contemporary imaging practices is recognized to be imperfect, it remains the most widely accepted exposure-risk model in radiology today [5–6]. Moreover, dose-response relationships in the setting of computed tomography (CT) were recently demonstrated in two large observational studies in the United Kingdom [7] and Australia [8], respectively, strengthening the validity of the exposure-risk relationship in imaging.

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Mathematically, a “linear no-threshold relationship” between an exposure and its associated risk means that: 1) every exposure is associated with some level of risk; 2) the relationship between risk and exposure is at all times linear (e.g. directly proportional); and 3) each incremental exposure imparts no greater risk than if a patient had never been exposed [9–12]. Taken together, these model characteristics imply that a patient’s exposure history should not be considered when a physician is making a new imaging decision. Using the same principle, risks from future potential imaging tests, in most cases, also should not be considered when deciding whether to order an imaging test “now.” While this line of reasoning falls directly from defining features of the LNT model – its linearity, and the absence of a threshold – the resulting practices seem counterintuitive [9–12].

While LNT model implications in the context of prior exposures have been described in the radiology literature, most physicians instinctively still feel that it is worse to perform an imaging test that involves radiation on a patient with a substantial prior exposure history [9–12]. In a recent survey study, the vast majority of radiologists (96%, 309/322) thought that according to the LNT model, patients’ past exposures *should* factor into current imaging decisions [12]. To our knowledge, how physicians should account for a patient’s future likelihood of imaging tests that involve radiation has not been similarly discussed. Based on LNT principles, even if a patient is likely to present repeatedly in the future for symptoms related to a known disease, the physician’s risk-benefit analysis for an imaging decision “now” should not take into account the future likelihood of imaging and associated radiation-induced cancer risks, a concept that is similarly difficult to reconcile with physicians’ clinical intuition.

In this educational piece, we describe an analogous circumstance of probability and decision-making – centered on a fisherman’s decision to embark on a fishing trip each day – to convey the fundamental, yet counterintuitive, elements of probability that govern why physicians should not use past or future potential radiation exposures to inform current imaging decisions according to LNT model principles. The example builds from related concepts in cognitive bias, probability, and survey research put forth by our research group and Durand and colleagues [9–12]. We then review widely discussed alternative radiation-risk models (linear-threshold, linear-quadratic, hormesis, and downward-sloping) and discuss why these models, for different reasons, ultimately point to the same practical conclusion in terms of how to operate clinically: namely, that previously incurred (or future suspected) radiation-induced cancer risks should not be used in current decisions [13–16]. We conclude with a vignette of a patient who has had multiple negative CT scans for the same clinical indication, and discuss why, even in this setting, previously incurred risks should not be used in a current risk-benefit analysis. Our goal is to provide an educational reference that can expand and anchor radiologists’ knowledge base in this area, so that they may serve as an effective resource within and outside of the radiology community.

The Fisherman’s Dilemma

Consider a fisherman who has just completed his 10th fishing trip. Because he sails on dangerous waters, each trip carries with it a chance of catching fish (supporting his

livelihood), but also a fixed chance of death. He has survived ten trips so far. Should he risk an 11th?

First, he can consider an easier question: the chance of dying within ten trips versus the chance of dying within eleven. Each additional trip he takes brings an additional chance of death, so he is clearly more likely to die within eleven trips than within ten. This can be determined before setting out on any trips. If the fisherman has a 90% chance of survival on each trip, he can calculate his probability of surviving two trips as $0.9 \times 0.9 = 0.81$. He again multiplies by 0.9 to calculate his chance of surviving three trips, $0.9 \times 0.9 \times 0.9 = 0.73$. He can calculate his chance of dying within three trips as $1 - 0.73$ (27%).

Table 1 shows the expected chances of survival or death for different projected numbers of trips. While the probabilities of survival and death *per* fishing trip are fixed, his *cumulative* probability of dying – the probability of dying within a given number of trips – continues to increase with more trips. The fisherman has a 65% chance of dying within ten trips ($1 - 0.9^{10} = 0.65$), and a 69% chance within eleven ($1 - 0.9^{11} = 0.69$).

It may be natural for the fisherman to assume that he has a greater chance of dying when he sets out on his 11th trip than he did when he set out on his 10th. He might feel like he is fated for an accident after surviving for so long, much like after several warm winters in a row people feel due for a cold one. However, this logic is incorrect – in deciding whether to take the 11th trip, if acting rationally, the fisherman should disregard risks incurred from the first 10. Instead of reflecting on the risk of eleven trips, he should only consider the risk of taking one trip *after surviving ten*. After ten trips, his chance of dying on the 11th remains 10% – the same as on every other trip.

In this example, the outcome of each trip is known – that is, the fisherman knows that he has survived. Put another way, when he has made ten trips, he knows his probability of surviving ten to be 100%, so he can calculate his probability of dying on the next as 10%. In contrast, in radiation-induced carcinogenesis, the development and effects of most cancers have an associated latency period of several years (5–10 years), meaning that it is impossible to know right away whether cancer development was induced from an imaging test such as a CT scan [5, 17]. Below, we show why this distinction does not affect the reasoning behind – and applicability of – the fisherman's example.

The Fisherman's Cards – An Analogy to Radiation-Induced Carcinogenesis

Suppose that the fisherman is offered the opportunity to defer death that would normally be incurred during his fishing trips – in other words, if the fisherman incurs “death” during one of his trips, he would die years later instead of at the time of the trip. The arrangement would be as follows: each time the fisherman goes on a trip, he picks a card from a deck of 10 cards and keeps it (Figure 1). The deck is replenished fully prior to each pick. He can never see what he picks, but if he picks a card with an “X” on it, he is fated to drown in the sea 5–10 years later. He initially accepts gratefully, but as the days go by, he and his family watch his pile of cards grow, and worry increasingly about whether he should go on his next trip.

However, as when each trip rendered the fisherman alive or dead, his growing pile of cards should not affect his decision to go on his 11th trip. As shown in Figure 1, regardless of how many trips he has taken, there are only two possible situations:

1. The fisherman has already drawn an X within ten trips.
2. The fisherman has not yet drawn an X by ten trips.

What do the cards tell him? If he has already drawn an X, the choice of whether to go on an 11th trip cannot affect his probability of death. If he has not, the probability of drawing an X for the 11th trip remains 10% – the same as for every other trip. Either way, his previous picks should not influence his decision to make the 11th trip, and cannot be mitigated by future actions. If fishing was worth the risk on the first trip, it should still be worth the risk now, and his growing pile of cards should not matter.

Implications for Use of Patient-Level Exposure Histories in Decision Making

Drawing an analogy to physician decision-making for patients with prior radiation exposure histories, each fishing trip may be viewed as an imaging test associated with radiation, and the fisherman's risk of death may be viewed as a patient's risk of cancer development. Key assumptions made in the fisherman's example are that: (1) risks of events are independent of one another; and (2) that there is no threshold beyond which the risks per trip change. These also hold true for the linear no-threshold (LNT) model [5]. While differences between the settings do not affect central implications for decision-making, it is important to keep in mind that the magnitude of radiation-induced cancer risks from imaging are much lower. For example, a 20-year-old man undergoing abdominopelvic CT at a typical effective dose of 10-mSv is projected to have a 1/1000 risk of radiation-induced cancer development over a lifetime [5].

Invoking practical examples, consider two 40-year-old women presenting to an emergency department with identical symptoms of appendicitis. One has a remote history of multiple prior pelvic CT scans performed in the context of hip and pelvic fractures years ago from a skiing accident; the other has no prior history of imaging. If an abdominopelvic CT scan is indicated for the patient with no exposure history, then according to the LNT model, an abdominopelvic CT scan is also indicated for the patient with a prior exposure history. Consider also two 40-year-old men presenting with epigastric pain after injuries from bicycle accidents that occurred a few days ago. One has a remote history of multiple abdominopelvic CT scans performed in the setting of lymphoma, cured years ago, and the other has no prior medical history. Similarly, if an abdominopelvic CT is indicated in the patient with no exposure history, then according to the LNT model, it is also indicated for the patient with a prior exposure history. The LNT model implies that in any clinical scenario, if the benefit of an imaging test exceeds its risks, then it is warranted, regardless of whether or not a patient has had prior radiation exposures [9–12].

The Fisherman's Cards and Future Imaging Risks

To understand the relevance of future imaging tests for current imaging decisions, consider again a fisherman who is trying to decide whether or not to go on his next fishing trip. In his opinion, today, the benefit (his compensation) “exceeds” his risk of death. However, he begins to think about the many trips he will need to take in order to support himself in the coming years, and about the large stack of cards that he will accrue. Should these factors weigh into his decision to go on a fishing trip today?

From a rational standpoint – and in most scenarios – the answer is “no.” His current risk, according to the LNT model, will not influence his future risks [5]. Therefore, if his risk-benefit ratio favors a fishing trip today, he should go. Put another way, risks associated with future fishing trips should not affect his decision today. Again invoking a practical example, consider a 25-year-old woman with Crohn's disease who presents to her physician with abdominal pain. Her physician is concerned about severe, active inflammation with a possible associated abscess. The physician considers two imaging tests for further evaluation: CT and MR enterography. After a careful weighing of risks and benefits – including the severity of symptoms, the slightly superior test performance of CT in this setting, and radiation-induced cancer risks – the physician determines that the current risk-benefit ratio favors CT over MRI in this patient's case. However, the physician knows that the patient will likely present with the same symptoms in the future, perhaps even 10–15 times more. Should the physician consider the cumulative risks of future CT scans in his current imaging decision?

Applying LNT principles, the answer is “no” – future risks should not be influenced by current imaging decisions, and instead merit consideration in their own risk-benefit analyses, when each specific scenario arises. As a corollary, if MR enterography were the preferred examination from a risk-benefit standpoint currently for this patient, then even in a Crohn's disease patient who is likely to have only one or two similar encounters (as opposed to 10–15), MR enterography would remain the preferred test – again, future risks should not be a factor.

As another example, consider instead two 25-year-old men: one with recently diagnosed Crohn's disease, and one with no past medical history. Both present to the emergency department with chest pain after binge drinking and repeated vomiting. Clinically, there is concern for esophageal tears, but fluoroscopic studies in both patients are equivocal. The physician responsible for both patients' care recommends chest CT scans for both, to evaluate for mediastinal air; however, in the patient with Crohn's disease, given the likelihood of future imaging, the physician asks the radiologist for a lower dose CT scan than is typically performed for this indication. Does this approach make sense? Again, according to LNT principles, the answer is “no.” If a standard chest CT protocol optimizes care in the patient with no past medical history from a risk-benefit standpoint, then a standard chest CT should also be performed for the patient in whom future imaging is likely. Again, as a corollary, if a reduced-dose CT optimizes care for the patient with Crohn's disease, then the patient without a past medical history should also receive the reduced-dose CT.

“Exception” Circumstances – When the Future is Known

Notable exceptions to the above reasoning occur when the cumulative risks and benefits of all future events are known at one point in time, e.g. *when an imaging decision is being made*. For example, what if the fisherman knew that although the trip’s benefits exceeded its risks today, in the long run, the cumulative benefits from all his planned trips could not outweigh the cumulative risks? Notably, this circumstance would violate our previous assumption of an unwavering risk-benefit ratio for each trip. In order for this situation to arise, for a proportion of future trips, the associated risk-benefit ratios would *have to favor not going fishing*, unlike today. If this knowledge were available to the fisherman today, then he may rationally make a decision that incorporates all known future risks and benefits and decide not to go fishing. Why is weighing cumulative future risks rational in this scenario, but not in the former? The key difference pertains to what the fisherman knows about the future. It is reasonable to weigh future cumulative risks with future cumulative benefits if both are known ahead of time. However, without a reasonable knowledge of both, a symmetric analysis of risks and benefits cannot be conducted.

In the Crohn’s disease example, or in any clinical setting where the benefits of imaging are linked to a patient’s specific symptoms (which dictate the frequency and nature of each encounter), it is generally not possible to estimate the future cumulative risks and benefits of imaging with accuracy. However, there are clinical scenarios where this is more feasible – for example, cancer surveillance imaging. Consensus decisions regarding CT frequency during cancer surveillance generally account for the projected cumulative benefits and risks of imaging [18]. Importantly, these recommendations are made under the assumption that the patients undergoing surveillance CT are asymptomatic. If a patient develops symptoms and undergoes “off-schedule” imaging to evaluate the etiology, then the initial risk-benefit analysis which informed the patient’s surveillance CT schedule must be reconsidered. This makes practical sense to most physicians – for example, the next surveillance CT may be reasonably skipped or delayed if the “off-schedule” CT covered the anatomic area of interest for cancer surveillance.

Implications of Alternative Radiation Risk Models

Most alternative exposure-risk models similarly imply that both previously incurred and future potential risks should not be incorporated in current imaging decisions, although for different reasons. In a comprehensive review, Brenner and colleagues discuss several alternative exposure-risk models for low-level radiation exposures, including a linear-threshold model, a hormesis model, an upward-sloping linear-quadratic model, and a downward-sloping model [13]. Here, we review each, and explain why each arrives at a common conclusion regarding the use of radiation exposure histories for prospective imaging decisions. Table 2 provides a summary of salient properties and decision-making implications for each exposure-risk model.

Linear Threshold Model

A linear-threshold model has been advanced by many critics of the LNT model [14]. Tubiana and colleagues argue for the existence of a “practical threshold” below which the

risk, if it exists, is so small as to be undetectable and clinically irrelevant [14]. No specific threshold has been supported by sufficient evidence [5]. They point to evidence in biological models of error-free DNA replication and elimination of pre-neoplastic cells, protective mechanisms that dominate at low doses [15]. The linear threshold model asserts that any exposure below a given threshold will incur no risk of radiation-induced cancer, and that each exposure above that threshold is linearly related to exposure, as in the case of the LNT model. This means that: (1) any new exposure will either be associated with no risk or a risk increase that is unaffected by previous exposures; and (2) any given exposure will not affect the magnitude of future exposures. The implication is that previously incurred – or future potential – radiation-induced cancer risks should not factor into current imaging decisions.

Upward-Sloping (Linear-Quadratic) Model

An upward-sloping linear-quadratic radiation-risk model was considered by BEIR VII investigators for describing solid cancers, and was recommended for evaluating risks of radiation-induced leukemia [5]. Unlike a linear model, the linear-quadratic model has a slope that increases as radiation exposures accumulate. If the exposure-risk relationship follows this pathway, then patients with a large exposure history would incur *incrementally* greater risks with each new radiation exposure. Furthermore, patients who were exposed “now” would be subject to proportionally higher cancer risks from future exposures. Put another way, theoretically, according to the linear-quadratic model, physicians should use prior (and future potential) radiation-induced cancer risks when making a current imaging decision. However, because the quadratic curvature is expected to be very slight at low dose levels, the model approximates the linear model in low-dose ranges [5]. Therefore, at a practical level, it is difficult to envision circumstances in which a physician could reasonably invoke this curvature to support an imaging decision that was inconsistent with LNT model assumptions.

Hormesis Model

A hormesis model asserts that low levels of radiation exposure induce mechanisms protective to oxidative damage, potentially reducing the risk of carcinogenesis below baseline levels [13, 16]. However, there is no consensus model for radiation hormesis, and no definite threshold has been identified below which radiation exposure is biologically protective; therefore, it cannot be definitively stated that exposure from a given diagnostic imaging test would fall in the protective range. If such an exposure did, then there would be no persistent risk incurred, which would again mean that cancer risks from previous – or future potential – exposures should not factor into prospective imaging decisions. In the event that an imaging test exceeded such a threshold, the cumulative exposure-risk relationship would likely be defined by one of the other models discussed in this section (linear, linear-quadratic, etc). If, beyond the hormesis threshold, the exposure-risk relationship was best explained by an upward-sloping curve, then a given exposure may affect the risk of subsequent exposures. In all other circumstances, previously incurred – or future potential – radiation-induced cancer risks should not factor into current imaging decisions, as implied by the LNT model.

Downward-Sloping Model

A downward-sloping exposure-risk curve – arguably the least accepted model among those discussed – has several potential explanations, some of which invoke population-level effects (a portion of the exposed population are disproportionately radiosensitive), and some of which invoke patient-level biological mechanisms [13]. Paradoxically, in the case of the downward-sloping model, incremental radiation-induced cancer risks *decrease* with each additional exposure. Here, again, previously incurred – and future potential – radiation-induced cancer risks should not prompt physicians to defer current imaging that involves radiation. While this model also suggests that prior exposures decrease risks associated with future exposures, this implication deviates far from other radiation-risk models, and the supportive evidence to justify related changes in practice is not adequate [13].

When a Patient Keeps Coming Back for More Imaging

Occasionally, an otherwise healthy patient returns repeatedly for imaging in a relatively short time interval. Consider a 30-year-old man who has unremitting abdominal pain over the course of a month, and who has undergone negative abdominopelvic CT scans three times within the past month for identical symptoms. He presents to the emergency department again, and his family is requesting an additional CT scan, as they remain concerned about the magnitude and acuity of his symptoms. His emergency medicine physician asks you, the on-call radiologist, about the combined radiation-induced cancer risks of the past studies, wary of the cumulative effects. Are cumulative prior exposures a concern in this situation?

According to the LNT model, the answer would still be “no.” In this patient’s particular circumstance, it may be logical not to proceed with another CT scan – however, the reason concerns a change in *benefit*, not a change in risk. If a patient has been imaged multiple times for the same symptoms, and if no corresponding pathology is detectable at imaging, it is reasonable to conclude, in many cases, that the benefit of an additional imaging test is lower than that projected for the first imaging test. If this benefit decreases to the extent that it falls below the low risks imposed by imaging, then an imaging test is no longer indicated. Put another way, there are diminishing returns – and thus decreased benefits – when repeated imaging is conducted for the same symptoms. Invoking this logic does not contradict LNT model implications, which concern radiation-induced cancer risks only.

This example highlights an important distinction between a patient’s *imaging history* and their *exposure history*. A patient’s imaging history – e.g. the imaging results for each test, and any related limitations and complications – should factor into prospective imaging decisions. As noted in the case above, a patient’s imaging history is oftentimes critical when making a prospective imaging decision. A patient’s *exposure history* – e.g. their cumulative exposures incurred – refers to a different metric, which, if applying LNT principles, should not factor into a prospective imaging decision.

Conclusion

Understanding how cancer risks from prior and future imaging should factor into imaging decisions that need to be made in the present can be cognitively challenging. Many of our initial instincts as physicians regarding how to use this information, which are grounded in what we feel is best for our patients, can actually prevent us from making the best imaging decisions [9–12]. In this paper, we have deconstructed the mathematics that explains why – according to the LNT model – radiation-induced cancer risks from prior imaging, and from future anticipated imaging, should not enter into a risk-benefit analysis for an imaging test that is under current consideration. We have also reviewed most alternative radiation-risk models, explaining why even if a physician believed in one of these models rather than the LNT model, it would be difficult to use these models to justify deferral of a specific imaging test (such as a CT scan) in the present, based on prior or future potential risks. Equipped with this knowledge, radiologists should be able to effectively address related decision-making challenges with policymakers, referring physicians, and most importantly, patients.

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Figure 1. The Fisherman's Cards

A fisherman takes 10 trips, and for each trip draws a card that corresponds to his risk of death from that trip – he can never see what he picks, but a card with an “X” will trigger his death years later. In trying to decide whether to take an 11th trip, there are two possibilities: he has either drawn at least one “X,” or he has not drawn any. In the first case, the choice of whether to go on the 11th trip cannot affect his probability of death. In the second, the probability of drawing an X for the 11th trip remains the same as for every other individual trip. Either way, his previous picks should not influence his new decision.

Table 1

The Fisherman's Dilemma: "Per Trip" vs. Cumulative Risks for 11 Trips

Fishing Trips	Probability of Survival (Per Trip)	Probability of Death (Per Trip)	Cumulative Probability of Survival	Cumulative Probability of Death
1	0.9	0.1	0.9	0.1 = 1-0.9
2	0.9	0.1	$0.81 = 0.9 \times 0.9$	0.19 = 1-0.81
3	0.9	0.1	$0.73 = 0.9 \times 0.9 \times 0.9$	0.27 = 1-0.73
4	0.9	0.1	$0.66 = 0.9^4$	0.34 = 1-0.66
5	0.9	0.1	$0.59 = 0.9^5$	0.41 = 1-0.59
6	0.9	0.1	$0.53 = 0.9^6$	0.47 = 1-0.53
7	0.9	0.1	$0.48 = 0.9^7$	0.52 = 1-0.48
8	0.9	0.1	$0.43 = 0.9^8$	0.57 = 1-0.43
9	0.9	0.1	$0.39 = 0.9^9$	0.61 = 1-0.39
10	0.9	0.1	$0.35 = 0.9^{10}$	0.65 = 1-0.35
11	0.9	0.1	$0.31 = 0.9^{11}$	0.69 = 1-0.31

Table 2

What the LNT and Alternate Radiation-Risk Models Imply Regarding the Use of Past (and Future Potential) Exposures in Physician Decision-Making

Radiation Model	Model Properties	Role of Past (and Future Potential) Exposures in Current Imaging Decisions
Linear No-Threshold (LNT)	Any amount of radiation exposure is harmful; exposure and radiation-induced cancer risk are linearly related [5, 13].	None: A new exposure is associated with the same radiation-induced cancer risk regardless of previous exposures.
Linear Threshold	Radiation exposures below a certain magnitude are not associated with cancer induction because cellular damage can be repaired. Beyond this threshold, radiation-induced cancer risks are directly proportional to exposure levels [13].	None: Exposures from imaging likely impart no single – or accumulated – radiation-induced cancer risks. A given radiation exposure may be below the threshold, which means that no radiation-induced cancer risk will be incurred. For exposures above the threshold, as in the LNT model, a new exposure is associated with the same radiation-induced cancer risk regardless of previous exposures [13].
Hormesis	Radiation exposures below a certain magnitude can have a beneficial, anti-carcinogenic effect [13, 16]. Exposure levels for individual imaging tests may be within the protective range, but there is no consensus threshold.	Likely None: Exposures from imaging may impart no radiation-induced cancer risks, although there is no consensus regarding the threshold that defines when protective effects no longer occur [13, 16]. For exposure levels above this hypothetical threshold, however, the cumulative exposure-risk relationship would likely be defined by one of the other described models, none of which strongly support the use of previously incurred (or future potential) risks for current imaging decisions. The primary instance in which previous exposures could have a slight effect would be if the exposure-risk relationship was linear-quadratic.
Linear- Quadratic (Upward-Sloping)	To a slight degree, past radiation exposures place patients at incrementally greater risk for radiation-induced cancer development with future exposures [5, 13].	Very little: The quadratic element (curvature) in this model is very small; at low levels of radiation exposure, the exposure-risk relationship closely approximates the LNT model, meaning that a new exposure is associated with <i>nearly</i> the same radiation-induced cancer risk regardless of previous exposures.
Downward-Sloping	Incremental radiation-induced cancer risks decrease as exposure levels increase [13].	Very little: A new exposure is not associated with increased radiation-induced cancer risk in the setting of prior exposures and could be associated with decreased risk, though operating under the latter assumption is not advised based on available evidence.