Implications of conflicting definitions of probability to health risk communication: a case study of familial cancer and genetic counselling

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Abstract

The question of what probability actually is has long been debated in philosophy and statistics. Although the concept of probability is fundamental to many applications in the health sciences, these debates are generally not well known to health professionals. This paper begins with an outline of some of the different interpretations of probability. Examples are provided of how each interpretation manifests in clinical practice. The discipline of genetic counselling (familial cancer) is used to ground the discussion. In the second part of the paper, some of the implications that different interpretations of probability may have in practice are examined. The main purpose of the paper is to draw attention to the fact that there is much contention as to the nature of the concept of probability. In practice, this creates the potential for ambiguity and confusion. This paper constitutes a call for deeper engagement with the ways in which probability and risk are understood in health research and practice.

Aust Health Rev 2007: 31(1): 24–33

What is known about the topic?
Although not necessarily recognised by health care practitioners, understanding of probability depends either on the definition of a given school of thought or on the conversational context in which it is employed. In practice, the interpretation that is applied to any given use of probability does not receive much attention, which is cause for concern when practitioners use probability to communicate with patients.

What does this paper add?
After describing the various interpretations of probability, ranging from frequency, degrees of belief, epistemic probability and tendencies, the impact of these various approaches on health care is examined. The author suggests there are implications for calculating clinical probabilities, including single event probabilities, as well as lack of clarity in communicating and managing risk among health care practitioners.

What are the implications for practitioners?
The author argues for a deeper understanding of the concept of probability to improve health research and practice.

THE MOVE FROM deterministic to probabilistic reasoning that seemed so radical some decades ago is now fairly well entrenched in health and medicine. It has even been said that this trend has gone too far and that *uncertainty* has become a valid analytical concept in and of itself.[1] In this casual acceptance of uncertainty in both routine and extra-ordinary events, there is often an almost flippant treatment of probability. This paper takes a close look at the concept of probability and the way in which it is used in health science. The domain of genetic counselling for possible cases of familial cancer is used to ground theoretical debate in practical health concerns. However, these arguments have implications beyond this setting and are relevant to all forms of health risk communication and management.

The paper begins with a cursory outline of some of the dominant interpretations of probability. Examples are provided of how each interpretation can be seen to manifest in either the management or communication of risk in familial cancer. In the second part of the paper, some of the practical implications of debates on the phi-

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losophy of probability are explored. It is argued that a deeper understanding of the concept of probability is likely to lead to improved estimates of risk, enhanced clarity in risk communication, and better decision making in risk monitoring and management.

Interpretations of probability: theory and examples from familial cancer

Questions as to the nature of probability are not new. The beginning of the formal (mathematical) theory of probability is generally argued to stem from studies of games of chance in the seventeenth century.[2] Since then, the philosophical interpretations underlying probability have been an ongoing topic for debate. Accounts of the historical development of probabilistic thinking are extensive[3-11] and the possible conceptualisations of probability are almost as varied as the number of probability theorists. An important conclusion from historical analyses of probability is that during the formative periods of probabilistic reasoning particular interpretations underlying probability were closely tied to the application in which probabilistic calculations were employed. More recently, however, interpretations have become utilised generally across applications and it has been pointed out that almost every interpretation "ever attempted by a probabilist is alive and well today in some form, however dubious its reputation in the intervening years."[7] (p. 271).

In the academic literature there is much contention and argument as to the "correct" use and interpretation of probability. While this paper makes reference to this ongoing debate, it is not the main concern to argue for or against any particular interpretation of probability. The fact is that, in practice, people draw on multiple constructs of probability.[12] This is particularly so in the health sciences. This discussion therefore focuses on documenting the most important ways in which probability is used in practice, rather than joining the fray as to how probability *should* be viewed.

Unfortunately there is difficulty even in categorising different approaches to probability, and theorists differ in the systems of classification they employ.[13,14] As this paper is geared primarily towards applications in health science, the different interpretations of probability are categorised broadly, based loosely on the system of classification of Gigerenzer[15] according to how they are actually used in health risk communication, rather than relying on any particular philosophical treatment. In addition, rather than refer to the original theorists who developed particular approaches to probability, where possible, more contemporary references are given that illustrate the ways in which probability may be presented to practitioners in the health sciences today. For more detailed discussions on the philosophy of probability and the origins of particular interpretations, see Gillies,[16] Fine,[17] Smithson,[18] and Weatherford.[14]

The context of genetic counselling is used to focus the debate (in particular, counselling for risk of familial cancer). Genetic counselling is a service offered to individuals and families that provides information and support regarding health issues that have a genetic basis.[19] Moreover, genetic counselling sessions have been identified as an important site of information exchange about genetic risk.[20] Risk communication in familial cancer is particularly challenging owing to the interaction of several dimensions of uncertainty. This complexity makes familial cancer an excellent case study to illustrate issues arising from theoretical debates on the philosophy of probability.

Probability as frequency — the long run frequency interpretation

According to this interpretation of probability "correct probabilities can only be determined empirically"[21] (p. 309), and probability estimates must be based on large numbers of observations. Assigning probabilities to individual events is meaningless and the result of any particular trial cannot be predicted. However, with an increasing number of trials, patterns of relative frequency can be observed. Relative frequencies are seen to converge to a "true probability", which can be ascertained ever more accurately with increasing numbers of trials.

Although, in practice, the rule of extrapolating the number of observations to infinity is not observed that strictly, the notion of associating probabilities and risks with frequencies is extremely common. In a very general way, this sense of probability can be seen to underlie such statements in cancer genetics as the rates of the occurrence of cancer in certain populations. For instance, based on knowledge of the prevalence of cancer, clients of genetic counselling sessions are informed that about one in three people in Australia will develop cancer in their lifetime. This is generally translated as a probability of 33% of developing cancer for any "average" Australian. Similar statements can be made for specific sub-groups of the population, such as that about 8% of women in South Australia are likely to develop breast cancer at some time in their lives. Again, this is often translated into a probability for a particular individual in a fairly straightforward way. In these kinds of statements, no reference is made to mechanisms or tendencies in the body that can be related to the risk figures quoted. This is not to say that information about the mechanisms of cancer is not provided to clients of familial cancer clinics (it generally is); however, the rationale behind these particular statements relies more on population statistics, rather than biological mechanisms.

Probability as a "best guess of what will happen" — degrees of belief

According to this interpretation, probability is viewed as a measure of belief (or confidence) in a particular statement or proposition, given some particular evidence (usually knowledge of similar situations). This conceptualisation of probability is generally associated with the use of Bayesian statistics, and its proponents present a range of arguments as to why it is superior to a frequentist view of probability.[22] Foremost among these arguments is that in many instances it is meaningful to assign probability estimates to events where no frequency data are available, as estimates can be backed by other forms of evidence. An example of this might be the first launch of a new type of rocket. Although it would be meaningless to assign a probability for a successful launch when operating within a frequentist framework, it is feasible to formulate a meaningful probability statement using a degree of belief interpretation. Evidence for the estimate might legitimately draw on such factors as the history of launches of other rockets or knowledge of the components of the rocket. A further advantage of the degree of belief interpretation is that it allows one to take into account the appropriateness of different types of conditioning evidence. One example is the assigning of a probability to the occurrence of a nerve impulse within 0.1 seconds, where we know that 70 out of the last 100 impulses occurred within 0.1 seconds and that the cell is dead. Clearly, the fact that the cell is dead is the more relevant piece of information upon which to base an estimate, and so a probability of zero, rather than 0.7 should be assigned. It follows therefore, that no single definite probability can be assigned to any proposition, as probability statements depend on the conditioning evidence used. For a more detailed treatment of this approach to probability see Jaynes.[23]

There are a number of ways in which this sense of probability can be seen to underlie statements or considerations in familial cancer. The most obvious is when a clinician makes statements about the likelihood of coming up with a definitive risk diagnosis for a client, in the sense of showing a degree of confidence in the ability to provide a certain outcome. When a client of a familial cancer service is identified as carrying a gene mutation that is known to predispose to cancer, the clinician is able to diagnose a certain level of risk for that client. However, if the client does not test positive for such a mutation, it is unknown whether the client is at "standard" population risk or whether there may be a predisposition owing to an as yet unidentified gene. It thus makes sense, here, to talk about the clinician's level of confidence (or degree of belief) in coming up with a diagnosis, and even putting a number to this concept (eg, "There is a 70% chance that we will be able to come up with a definitive risk diagnosis for you.")

Another sense in which the concept of probability as a "degree of belief" is used in familial cancer is when "high risk" is diagnosed owing to the pattern of cancer incidence in a given family. In the absence of a genetic test, most clinicians follow national guidelines as to the criteria that an individual needs to meet for a certain cancer risk level to be diagnosed.[24] For instance, a high risk of breast cancer may be diagnosed for a woman if three women in her immediate family have all developed breast cancer at a relatively young age. It is important to note that the "high" probability of a future occurrence of breast cancer here is not based on simply counting the relative frequency of cancers in that family and then translating this directly into a probability. Rather, owing to certain criteria the level of risk is inferred. And although these criteria are objective, in the sense that they are based on material (medical) events that can be observed, the process of inference underlying the probability statement has a subjective element to it. Moreover, this probability is subjective in the sense that the clinician may revise the risk estimate with additional information. For instance, if it can be shown that the incidences of cancer in the other family members were caused by environmental factors, any members of the family who were not exposed to the same problem may be deemed at standard population risk.

Probability as a way of investigating the underlying structure of the environment — epistemic probability

The term "epistemic probability" has been used in a number of different ways in the philosophy of probability. As a specific interpretation of probability (propagated primarily by Laplace) epistemic probability no longer holds much sway.[7] In its extreme form, this interpretation posits that all uncertainty is simply due to insufficient knowledge or the presence of errors in the process of gathering information. Taken to its logical conclusion, therefore, we would move ever closer to a truly deterministic picture of the world through refining our knowledge and scientific methodologies. This extreme view has been largely discredited on a number of grounds. There is a sense, however, in which an epistemic conceptualisation of probability should be recognised, which involves the use of probability to infer the likelihood of some description or model being an accurate description of the world. Examples of such epistemic uses of probability can be found in the processes of testing a model or hypothesis in science, or evaluating the likelihood of the accuracy of a medical diagnosis. This sense of probability has much in common with a degree of belief interpretation (in particular, when formalised mathematically), but it is worth listing separately to draw attention to two factors:

- There are different implications for the use of probability in "figuring out the most likely correct description of some aspect of the world" as opposed to its use to quantify the likelihood of a particular event occurring in the future.
- In some instances it is valuable to distinguish between probability statements based on collective knowledge versus individual knowledge. Although probability statements according to the degree of belief interpretation are not necessarily about an individual's beliefs,[23] in practice one finds that "subjective probabilities" are often used to describe individuals' cognitive states (most notably any reasoning based on the work of Kahneman and Tversky[25]). It is thus appropriate to conceptualise a distinct sense of probability that involves knowledge of a more collective character.

An example of such an epistemic sense of probability can be found in its use in hypothesis testing. In this context, probability is not used in the first instance to make predictions about the future but to evaluate the quality of a hypothesis about some aspect of the world. There is also a public or collective rather than an individual subjective character to this use of probability. That is, a P value of less than 0.01 is generally not interpreted as a particular scientist's degree of belief about the validity of a hypothesis. Nevertheless, these probability statements do have a "best guess" character as they rely on knowledge and inference to assess a "most-likely" description of the world.

In cancer genetics, this sense of probability is evident when one considers the chances of inheriting a predisposition to cancer. If an individual is known to be the carrier of a gene mutation that is associated with an increased risk of breast cancer, there is a 50% chance that that person's siblings are also carriers of the same gene mutation. This reasoning relies on current knowledge of genetic mechanisms and the assumption that only one parent is the carrier of the mutation. The probability statement is epistemic, in the sense that it deals with knowledge about an event that has already occurred. Whether the sibling does or does not carry the mutation was determined at conception — it is simply that the carrier status is not known at this point in time. It is thus a statement about the current "state of the world" and not a prediction of the future (although it can be used to derive other probability statements that do make predictions about future events).

Probability as tendency for things to happen — propensities

In contrast to interpreting probability as a relative frequency extrapolated to infinity or as a degree of belief in a certain proposition, Karl Popper argued that it should be understood as an objective quality inherent in an object or situation. For example, the probability of rolling a six on a fair die is 1/6, not because someone believes it to be so, or because the die has been thrown a large number of times and empirical evidence points to a convergence of 1/6. Rather, the probability is 1/6 because of the nature of the die and its inherent properties, such as symmetry. Probability is thus seen as a propensity of the die to behave in a certain way. What distinguishes this interpretation from others is that probabilities are accorded a level of "realness" beyond a state of knowledge (degree of belief; epistemic) or an abstract number hypothesised for an infinite number of trials (frequentist). Rather, the propensity theory states that "There exist weighted possibilities which are *more than mere possibilities*, but tendencies or propensities to become real: tendencies or propensities to realize themselves which are inherent in all possibilities in various degrees and which are something like forces that keep the statistics stable."[26] (p. 12)

In familial cancer, this construct of probability is usually evident when we talk of a particular person having, say, a 70% chance of developing cancer. Although some statisticians argue that even these statements about individuals should be understood in terms of frequencies, the use of such statements in practice generally implies some underlying mechanism that results in a tendency to develop cancer. That is, while frequency data may be used to achieve risk estimates for these tendencies, the implication is that the risk is associated with a property that is internal to the body of the client, a genetically based mechanism that increases the body's propensity towards developing cancer.

As this is only a cursory overview of debates about the interpretation of probability, there are some limitations to this discussion that should be acknowledged. In particular, only approaches described by Gillies[16] as "monist" were discussed. Most theorists who adopt a monist stance on probability would argue that their chosen view on probability is able to account for all of its uses and that the different "senses" of probability discussed in this paper do not really exist. Such arguments are generally substantiated by operationalising probability statements in such a way as to fit the theorist's interpretation of choice. The fact remains, however, that proponents of any of these interpretations cannot agree as to which is the "correct" interpretation of probability. Fortunately, there are many theorists who adopt pluralist approaches to probability, in which they explicitly allow for more than one valid interpretation of probability (see Gillies[16] for a more detailed argument in favour of adopting a pluralist position).

Practical implications of using different interpretations of probability

What is the relevance to health science of calling attention to debates on the philosophy of probability? In this final section of the paper, this question is addressed by identifying some of the issues in which the interpretation underlying probability statements may have an impact on how a problem is dealt with or, in the context of health-risk communication, on the subsequent behaviour of individuals. This discussion is not intended to be comprehensive but to highlight some issues that may be of interest to health professionals.

Implications for data collection and statistical analysis — do different interpretations lead to different answers for the same problem?

The first issue is this: one may argue as to the correct interpretation of probability, but when the calculations are done, do different interpretations actually yield different results? There is contention even on this point.[27-30] Although the details of this debate go beyond the scope of this paper, it is appropriate to point out at least one practical example in which the particular interpretation of probability that is applied to a problem affects the outcome of a calculation.

Gigerenzer[15] related that during a visit to Daimler-Benz Aerospace (DASA [Deutsche Aerospace AG]), he noticed that DASA calculated the "security factor" for a successful rocket launch to be 99.6%. Gigerenzer observed that this estimate did not reflect the fact that 8 accidents had previously occurred out of a total of 94 launches. When queried about this, DASA accounted for this discrepancy by stating that security ratings were not based on "counting accidents", but on design features of individual parts of the rocket. Gigerenzer argues that DASA's calculation was based on a propensity interpretation of probability, and that a frequency interpretation (based on the relative frequency of successful launches) would have resulted in a very different security factor. And, perhaps tellingly, the security factor according to a calculation involving relative frequencies would have been significantly lower (91.5%).

Conflicting interpretations is also a bone of contention in debates between "orthodox" and "Bayesian" statisticians. While the former generally subscribe to some form of the long run frequency interpretation, the latter generally subscribe to one of a range of variations of the degree of belief interpretation. Although the interpretation that is attached to probability is generally not central to the debate,[31] the debate highlights the fact that the interpretation of probability that guides any given study has implications not only for data analysis, but for what constitutes data in the first place. For instance, according to the long run frequency interpretation it is implicit that frequency data is required in the formulation of probability statements. In contrast, frequencies do not constitute the only form of evidence for either a degree of belief or a propensity interpretation. The conceptualisation that underlies any given study therefore places significant parameters around data collection and measurement.

The implications of this observation for the health sciences are self-evident. Most studies in the field involve probability, and so attention should be given to the construct that is employed. In addition, most health professionals are not necessarily trained statisticians. Therefore, most probabilistic calculations are likely to be performed using existing models that already incorporate implicitly a given interpretation of probability, which may or may not be appropriate to the problem. A deeper level of engagement with the construct of probability employed in any given situation is therefore likely to improve diagnoses of risk.

Does it make sense to talk about the probability of a single event?

A more subtle point is that some interpretations of probability allow certain types of probability statements, whereas others do not. One such case is the use of probabilities to refer to unique events (ie, no frequency data are available for the event). In particular, a long run frequency interpretation simply does not allow for these kinds of statements. Probability statements must be based on a series of events whose distribution can be calculated, otherwise the concept of probability holds no meaning. However, in the frameworks of both degree of belief and propensity interpretations, it does make sense to formulate probability statements about single events. From a degree of belief perspective, a probability can be interpreted as a measure of the confidence that a person has in the truth of a statement. As there is no requirement for this statement to refer to a distribution of prior events, it is acceptable for the degree of belief to refer to a particular event. Single event probabilities are also accommodated within a propensity interpretation, as probabilities are regarded as tendencies of physical systems to behave in certain ways. The fact that such a statement refers to a unique event may mean that it is more difficult to substantiate, but it does not mean that such a statement can not be made. (For a more detailed discussion about single event probabilities see Gigerenzer[15,27] and Weatherford.[14])

In familial cancer, this issue surfaces when communicating to individuals the probability that they will develop cancer. From the perspective of a clinician, it makes sense to think of any given client as one among a distribution of individuals. A frequentist view of probability thus lends itself to understanding the problem from this perspective. However, from the perspective of an individual, who is concerned with the question of whether he or she will develop cancer, this perspective may not be appropriate (if not for rational reasons, then at the very least for emotional reasons). The most pressing concern of the individual faced with the prospect of familial cancer is surely whether they or a particular member of their family will develop cancer. As a frequentist perspective does not allow for viewing risk in this way, it may be more appropriate to communicate risk in ways that imply degree of belief or propensity-type interpretations of probability.[32]

Implications for the management of risk

The management of risk is a further step in which the particular conceptualisation of probability may play an important role. In general, debates on the philosophical basis of probability have not featured highly in the literature of probabilistic risk assessment, with the relative frequency and logical schools of probability generally holding sway.[18] However, changes are afoot, and increasingly these positions are being challenged. Consequently, debates as to appropriate norms for defining and substantiating probability statements are becoming relevant.

Quite distinct from actual risk assessments, the communication of risk management strategies is often highly sensitive to the construct of probability underlying any given strategy. In a study of genetic counselling transcripts, it was found that talk about physical interventions to reduce cancer risk was inevitably associated with probability statements that framed risk in a physical (propensity) way.[33] In contrast, talk about refining risk estimates through gathering additional information or conducting genetic tests on a person's DNA was inevitably associated with framing risk in an epistemic way. This observation becomes relevant when one considers what it means to reduce a probability. When talking about risk in the physical sense, a reduction in the probability associated with cancer means changing physical circumstances. That is, through such interventions as prophylactic surgery or certain medications, the risk (propensity) of cancer may be reduced. In contrast, when talking about risk in an epistemic way, the risk (best guess) associated with cancer is reduced through gaining particular information. For instance, a clinician may consider an individual as high risk for bowel cancer owing to that person's family history of cancer. However, should this person undergo a genetic test, and this test indicate that the person did not inherit a genetic mutation that placed others in the family at risk, the probability of cancer may drop to medium or even low risk.

Over the whole corpus of genetic counselling sessions examined, health professionals were observed to engage with four categories of risk management.

- *Refining risk estimates (measuring risk)*. Conducting a genetic test is an example of a strategy that falls into this category. Essentially *risk management* here constitutes reducing the uncertainty that is associated with a risk estimate. However, no matter how precise such a risk estimate becomes, this kind of management of risk does not change the underlying physical factors that constitute the risk in the first place.

- *Reduction of the likelihood of occurrence of an event (reducing risk).* This sense of risk management involves changing physical circumstances in such a way as to reduce the tendency of cancer occurring. An example of such a strategy is prophylactic surgery. Removal of breast tissue, for instance, reduces the possibility of breast cancer occurring.
- *Minimising the risk that the opportunity of successful medical intervention will be missed should cancer develop (detecting the disease).* If an individual does actually develop cancer, the disease can only be treated if it is detected. It is thus important to minimise the risk of not detecting the disease (examples of strategies to manage this risk for breast cancer are regular mammograms and breast self examinations).
- *Taking steps to optimise successful treatment chances should cancer develop ("optimising" treatment of disease).* This final category is closely associated with the previous one. However, in this sense of risk management there is no engagement with the probabilistic aspect of risk at all. Rather, the focus is on the potential manifestation of disease itself. In familial cancer, surveillance not only decreases the chances of missing cancers, it also offers to decrease the severity of the consequences should cancer develop. That is, the earlier a cancer is detected, the easier it is to treat. It is thus important to make the following distinctions: when a woman considered at increased risk of breast cancer undergoes a mammogram, she is not reducing the probability that she will develop cancer; she is also not refining the estimated likelihood that she will develop cancer. Rather, the mammogram assists in detecting cancer as early as possible to maximise chances for successful treatment.

Clearly, all four categories are essential components of a comprehensive risk management program. The point here is that three categories draw on different interpretations of probability (arguably, a form of subjective interpretation in the first, a form of propensity interpretation in the second, and an epistemic interpretation in the third). In contrast, the fourth category does not involve any direct reference to the probability of developing cancer whatsoever, but rather represents an effort to minimise the severity of the consequences of cancer should it develop. When a health professional communicates risk or educates about risk management options without being able to distinguish clearly between different constructs of risk, the potential for miscommunication and confusion is high.

Rhetorical implications

An issue that has not received much attention is the impact of different interpretations of probability on the communication of risks. Most theorists concerned with the philosophy of probability confine their arguments to mathematics and statistics and rarely consider the communication of risks. In practice, it is clear that the discourse of health professionals (as well as almost everyone else, for that matter) contains references to probability that stretch across a range of interpretations.[12,34] Recent studies have demonstrated that this can lead to a high degree of conceptual conflation in medical risk communication.[35,36] Unfortunately, there is no quick fix to this problem. Improving the clarity of risk communication may require that practitioners develop a much deeper awareness of the nature of uncertainty and probability, and the way in which they are treated in specific health contexts.

Conclusion

The term "probability" does not have a natural referent.[37] What it denotes, therefore, depends either on the definition of a given school of thought or on the conversational context in which it is employed. In practice, the interpretation that is applied to any given use of probability does not receive much attention. In fact, most health professionals who routinely employ probability for estimating and communicating risks or for implementing risk management programs are not even aware that there is a debate about the nature of probability.

In general, debates regarding the philosophical foundations of probability are not associated with the health sciences. In this paper, the case of genetic counselling was used to ground the debate in practical concerns relevant to health practitioners. However, the implications of this debate clearly go far beyond the setting of genetic counselling. In particular, the philosophical interpretation that underlies a probability statement has consequences for:

- The calculation of risks
- The design and implementation of risk management procedures
- The rhetorical impact of risk communication
- The behaviour (and decision making) of clients following diagnoses of risk
- The way in which practical issues in the "real world" (rather than tightly controlled laboratory experiments) are taken into account when calculating probabilities

In short, in spite of the often abstract nature of debates concerning the philosophy of probability, there are very practical consequences that follow from the way in which probability is understood (or misunderstood). Although it is not possible to explore these implications beyond the genetic counselling context in a single journal article, it should be evident from the arguments presented above that a deeper understanding of the concept of probability is likely to improve health research and practice.

Acknowledgements

Thanks to Mark Mackay, Rebecca Grivas, and two anonymous reviewers for helpful comments on an earlier version of this paper. The research was conducted for a PhD dissertation which was funded through an Australian Postgraduate Award scholarship.

Competing interests

The author declares that he has no competing interests.

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