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Human Reliability Analysis of Radiotherapy Procedures Using Bayesian Networks

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This paper highlights and models the most important steps in radiotherapy procedures by identifying possible modes of human errors in them. The most common form of radiotherapy is external beam radiotherapy or teletherapy, where the patient sits or lies on a couch and an external source of radiation is pointed at a particular part of the body. The other form is brachytherapy in which the radiation source is inside the body. An approach based on Bayesian networks was used to model the most relevant steps of teletherapy and brachytherapy. Also, interactions between individuals and between humans and complex systems, considering the dependencies between events and performance shaping factors (including organizational factors) can be realistically modeled. Finally, as a technique for the quantification of Bayesian networks, an expert opinion elicitation procedure was used since there was no available database that could be used. In the case of teletherapy, observing only the stages of prescription, planning and execution, it appears that the step which increases the success probability the most, after consideration of preventive measures is implementation, which is in agreement with cases of errors and accidents reported in the literature. Related to brachytherapy, the most relevant factor was the use of equipment, whose increase in success probability, after consideration of preventive measures was 39.8%, demonstrating the importance of a continuous specific training.

1. Introduction

Facilities that work with hazardous materials, like nuclear facilities, have risk management systems that aim to prevent or minimize the occurrence or development of accidents. Such systems are based on physical barriers or protective barriers (primarily equipment and systems, such as jackets) plus human aspects, such as the use of procedures and training of professionals.

Human Reliability Analysis (HRA) has been an important element in the analysis of the risk that complex systems impose on operators and the general public. This tool is often used in nuclear power plants. However, this culture is not yet widespread in other installations that utilize radioisotopes, such as industrial and radiotherapy installations.

Thomadsen et al (2003) and IAEA (2006) use techniques or suggest Probabilistic Safety Analysis (PSA) tools, as fault trees and event trees, though such tools do not allow the tracking of key factors that influence human failures, factors that limit human performance, such as excessive work load, environmental conditions, and stress. Souza et al. (2001) describe some human errors committed in teletherapy and brachytherapy procedures and make clear the importance of the context in some failures that have occurred.

Teletherapy is a form of radiotherapy where a radiation source is external to the patient. Equipment is used with X-rays (linear accelerators, X-ray machines) and radioactive sources (usually ^{60}Co). Brachytherapy is a short distance treatment, where an encapsulated source (or source group) is used to release β or γ radiation within inches of the tumor.

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Some radioactive accidents have been reported in the technical literature with man as the root cause. Souza et al. (2001) point out some errors in radiotherapy treatments that directly affect patients. It is quite convenient to study a methodology that can be applied specifically to failures.
Radiotherapy is very dependent on human performance. A large number of steps, tasks and subtasks must be performed several times in a day's work and they are not similar from one patient to another. Many people work together, contributing a small part of the process. Professionals from various disciplines must interact and this, according to IAEA (2000), may increase the occurrence of errors during the process.
The method addressed in this research is based on established techniques of expert elicitation and Bayesian networks, which enables the quantification of dependencies of the variables involved. The case study was conducted through field research in the field of radiation therapy at the Clementino Fraga Filho University Hospital, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil (Gomes, 2011). The aim of this case study was to understand the context of HRA and the constraints related to the activities of brachytherapy and teletherapy developed.

2. Methodology

At first, we studied the protocols of teletherapy and brachytherapy treatments, the people involved and the equipment used. In a second step, we checked the possible scenarios for human errors that could occur in these procedures. Bayesian networks can include the failure context and assess dependent events, namely those events which significantly contribute to the case analyzed.
The next step was to identify the factors that most influence errors (performance shaping factors) including dependent factors, such as the influence of stress on technician's workload. We also analyzed how these factors affect the probability of failure where failure is meant by a radiotherapy accident in which the patient receives an unprescribed dose.
With the scenarios identified, we could model the entire procedure, using the techniques of expert elicitation and Bayesian networks.
The expert elicitation process should be systematic for all issues. The eight steps that were followed in this work, based on NUREG -1150 (NRC, 1989), NUREG - 6372 (NRC, 1997), and Ayyub (2001), are shown in Figure 1.

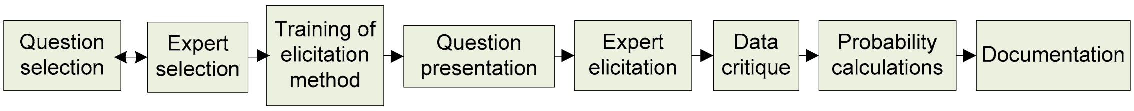

Figure 1: Expert elicitation process

After identifying all the factors of interest and the modeling, the next step is to quantify the desired probabilities in order to estimate the impact of human factors in different contexts. For this, we used questionnaires based on Bayesian networks presented in section 3 and applied to different groups of professionals: radiotherapy physicians, medical physicists and radiology technicians. It is worth noting that this study was based on interview techniques already mentioned, and that professionals were designated by a code, thus ensuring information confidentiality. The main factor for expert selection was their working time with radiation. The elicited professionals had 11 years experience on the average.

3. Bayesian networks

Bayesian networks are acyclic graphs directed by nodes and edges. Each node represents the probability that a given variable is in certain states. If a node A is dependent on a set of nodes B_i, the probability is calculated using Bayes' Theorem, given the conditional probabilities $P(A|B_i)$ and the joint probability (Jensen, 1996). In this work, Bayesian networks were set from information from IAEA (2000) and the software used was Netica, a trademark from Norsys Software Corporation.
The Bayesian network for the brachytherapy procedure was simplified in order to obtain conditional values for quantification. Factors related to equipment, training and source configuration were coupled to the node equipment for better observation of the interaction between them. For the source configuration the prevailing factors were: fixing the source in the patient to maintain its position throughout the procedure, source sealing and storage, including source identification. These were the most relevant factors for the accidents and incidents studied in IAEA (2000). Finally, for the brachytherapy treatment to be successful, it is essential that the schedule is suitable and well executed. For the execution to be properly done there

must be good communication between the professionals involved. Figure 2 displays the Bayesian network created.

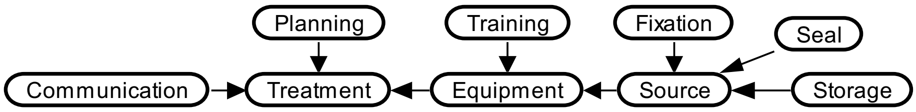

Figure 2: Bayesian network for brachytherapy

In Figure 3 we can observe the Bayesian network created for the teletherapy treatment. Chronologically, the stages of teletherapy are: prescription, planning and execution. In the prescription step, one can observe the node communication, while for the other steps this node does not appear. This is true not because communication is not important in further steps, but for this step it is decisive in a scenario where failures occur, in accordance to IAEA (2000).

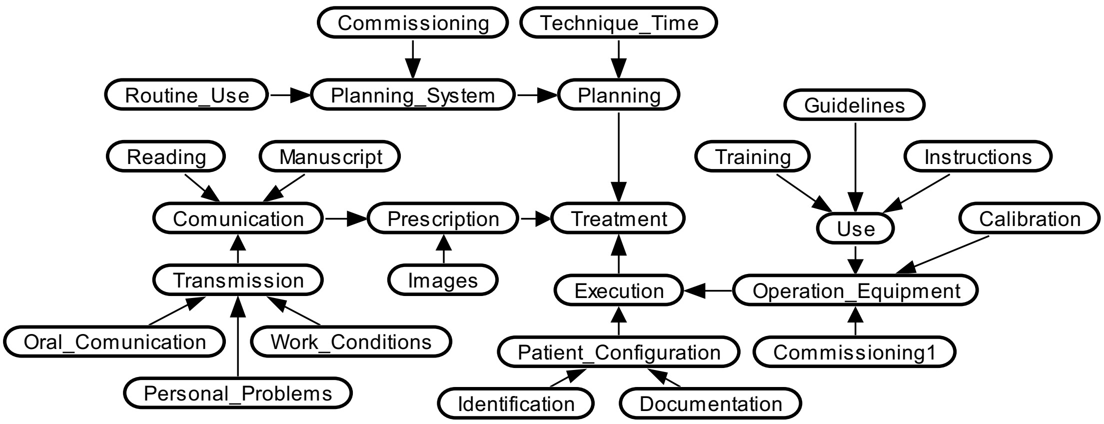

Figure 3: Bayesian network for teletherapy

Posterior probabilities are obtained from the same questions asked to experts to obtain prior probabilities, but taking into account prevention measures presented in IAEA (2000) for the prevention of accidents, which include the identification of radiotherapy critical safety steps and activities. Some preventive measures to minimize serious consequences related to poor communication are: identifying and sending all the rules for communication; clear allocation of employee responsibilities, including written descriptions, and procedures written in a clear and concise way for safety communications in critical situations.

Accidents related to equipment failures have a low frequency of occurrence in relation to other sources of accidents, however, the consequences can be severe and many patients may be affected. Some measures for accident prevention and mitigation of the consequences can be taken, such as: common-cause failure analysis, used to ensure that a common-cause failure does not render a redundancy inoperable; design of components and systems based on the concept of defense in depth; and inclusion of abnormal operating conditions in testing prototypes.

Problems of human-system interface can occur due to failure to understand the functioning of the equipment, including the meaning of alarms and signals that indicate a malfunction. Some considerations when observed can minimize failures related to this field, for example: to assume as true signals that are initially inconsistent and indicate the worst case and then investigate their consistency; consideration of human-system interface in the clinical environment in designing equipment; and specific training for recognition of abnormal and contradictory signals.

Bayesian networks for brachytherapy and teletherapy, prior probabilities and networks considering these measures for preventing accidents and posterior probabilities are discussed in section 4.

4. Results

Regarding brachytherapy, the Bayesian networks can be seen in Figures 4 and 5. The factor that had the greatest relevance in the analysis was the equipment use, which increased the "appropriate use" state probability once preventive measures were considered by 39.8%. This figure shows the importance of equipment appropriate use, which is well known, but specific and continuing training is to be highlighted.

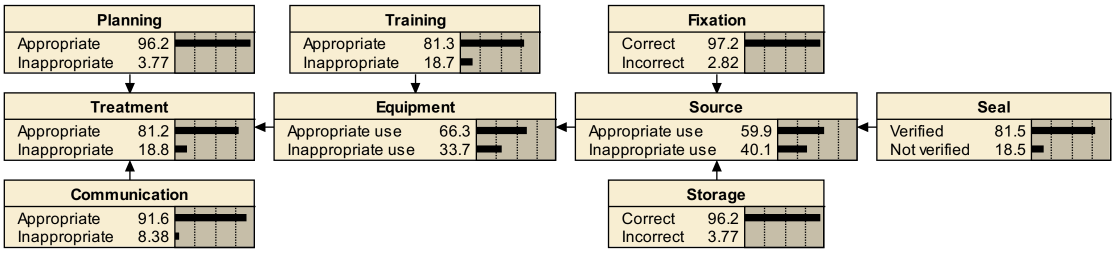

Figure 4: Bayesian network with prior probabilities for brachytherapy treatment

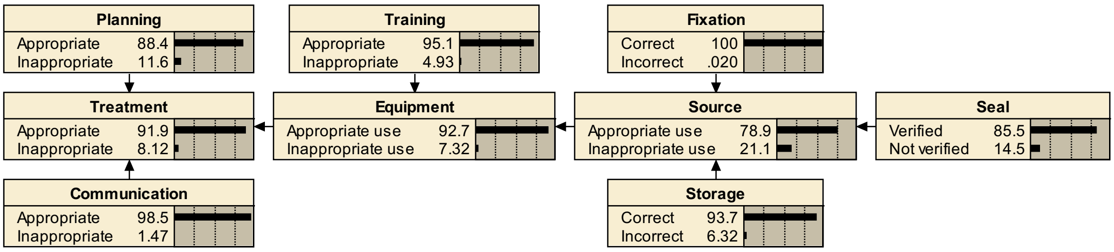

Figure 5: Bayesian network with posterior probabilities for brachytherapy treatment

For each node depending on other(s), tables of conditional probabilities were derived from expert elicitation of specialists, as displayed in Table 1.

Table 1: Prior probability for adequate source use

	Seal			
	Verified		Not verified	
	Fixation		Fixation	
Storage	Appropriate	Inappropriate	Appropriate	Inappropriate
Appropriate	0.999	0.990	0.050	0.013
Inappropriate	0.718	0.755	0.024	0.018

Quantified Bayesian networks for the prescription, planning and execution stages in teletherapy can be seen in Figures 6, 7 and 8, respectively, with their related prior probabilities.

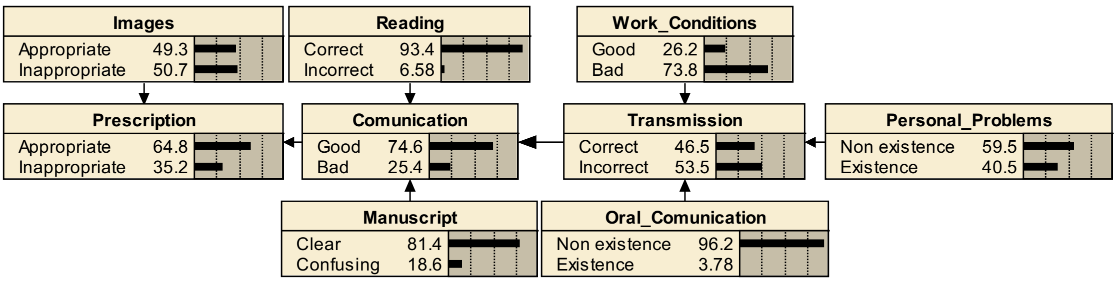

Figure 6: Bayesian network with prior probabilities for the prescription phase of the teletherapy treatment

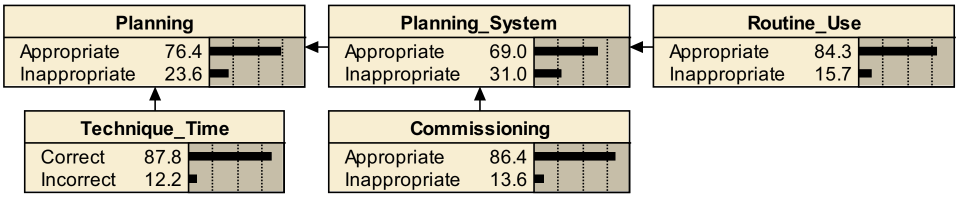

Figure 7: Bayesian network for the planning phase of teletherapy treatment.

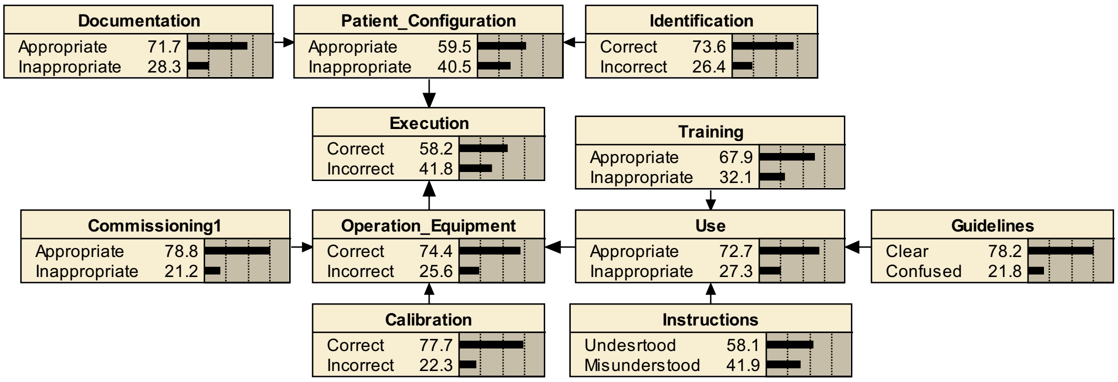

Figure 8: Bayesian network for the execution phase of teletherapy treatment.

In the prescription phase of teletherapy treatment, the most affected node due to the variation of measures for prevention of accidents was "information transmission", being poor working conditions that cause distractions and loss of concentration its most important contributors, which is in agreement with IAEA (2000). The consideration of extra safety measures resulted in an increase of 55.27 % for the transmission of accurate information state probability, resulting along with other factors, in an increase of 13.12 % for the probability of the proper state of the prescription treatment node.

At the planning stage there was a dependency relationship between the planning system (which involves commissioning and data entry) and treatment planning. The planning system is a more significant failure source than the choice of technique and calculation of treatment time, and it is very sensitive to accident prevention measures. When these were considered, the proper state planning system probability increased by 41.59 %, strongly influencing the increase of 19.24 % of the appropriate state of the treatment planning node.

In the implementation phase of the teletherapy treatment the most relevant nodes were:

- patient configuration probability, which suffered an increase of 45.82 % with specific measures for preventing accidents such as, for example, checking of documents for more than one worker;
- proper equipment operation due to its proper use, reflecting a probability increase of 34.78 % for the correct operation state;
- training, whose adequate state probability increase was 29.33 %. Continued training as well as periodic updates of professionals involved mainly in the implementation phase of treatment is an effective measure to prevent failures.

5. Conclusions

One purpose of the study was to highlight and model the most important steps in radiotherapy procedures involving human actions. This goal was achieved from modeling via Bayesian networks, in which one can clearly observe the causal relationship between the various stages of the procedures analyzed.

Bayesian networks were built in a simplified way due to the limitation found in this approach, since quantification depends on conditional probabilities. However, simply but realistically, the most sensitive factors to human actions and how measures for preventing accidents become preponderant for minimizing human error were observed.

The analysis via Bayesian networks proved adequate and useful for the observation of the causal relationship between the various phases of treatment procedures with teletherapy and brachytherapy

techniques. It was possible to represent the connection between the steps of the analyzed procedures and to see how certain factors, for example, continued training, is fundamental in the utilization step of the treatment equipment.
This work faced other limitations on the method used itself. Expert elicitation, besides being a totally subjective process, is a new technique for the professionals involved, and somewhat exhausting. In this sense, the importance of training on the elicitation method was clearly demonstrated. This technique was chosen because there are no other means of obtaining data for the quantification of Bayesian networks.
It is worth stressing that these results do not refer to the risks of the analyzed procedure. The analysis only considers human factors, excluding issues relating to failure rates of the equipment used. Thus, our results reflect only the sensitivity of the procedures to human actions, i.e., demonstrate what the most relevant factors for minimizing human error are. This analysis is extremely valuable when it is necessary to carry out improvements to minimize incidents and accidents or on a cost-benefit analysis in a radiotherapy facility.

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