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Bayesian Networks Applied to Risk Modeling of Depressurized Flight at High Altitude

Moacyr Machado Cardoso Jr.[1]**, Bruno Cândido de Paula**[1]**, and Thyago Leal Silva**[2]

[1]*Department of Space Sciences and Technologies, Technological Institute of Aeronautics, Brazil*

E-mail:, moajr1964@gmail.com , candidoita21@gmail.com, thyago.l.silva.10@gmail.com

Abstract

This study analyses the health risks of high-altitude parachute launch missions, such as hypoxia, decompression sickness, and otological barotrauma, using Bayesian probability networks to assess and mitigate these risks. All of these risk factors arise from the characteristics of the mission, which occurs in an environment hostile to human physiology in terms of pressure and temperature. Bayesian networks are effective tools for modelling uncertainties and diagnosing complex systems, aiding in event planning and decision-making. In the study, three Bayesian networks were constructed using Netica software, with steps for defining causes, effects, and causal relationships, in addition to determining probabilities. For the networks assembled, the results showed that hypoxia presents a risk of serious damage of 1 in 10,000 flights, while decompression sickness has a lesser impact, with a risk of moderate damage of 1 in 50,000 flights. Otological barotrauma presents a risk of moderate damage of 1 in 250 flights. In some of the analyses, the human factor proved to be an essential element in mitigating risks. Finally, the effectiveness of Bayesian networks in risk assessment is highlighted, suggesting the acquisition of more data to consolidate the probabilities employed, and proposing studies that include logistical and operational aspects in the planning of missions of this profile.

Keywords: Bayes Net 1, HALO 2, Risk Assessment 3, Depressurized Flight 4

1 Introduction

During the Second World War, the use of paratroopers and airborne equipment drops to penetrate enemy territory was a notable strategy, with the primary objective of seizing strategic areas and disrupting enemy supply lines [1]. As techniques and equipment for such operations improved, different tactics were developed, such as high-altitude free-fall and high-altitude cargo drops. These are military operations in which paratroopers or cargo are released from altitudes above 12,000 ft with the aim of enhancing stealth, thereby increasing the chances of success for a surprise attack [2].

Given that these operations take place in an environment hostile to human physiology, particularly in terms of pressure and temperature to which participants are exposed, there is a need to conduct complex risk management, especially regarding the health of those involved. The sources of hazard are varied and include factors ranging from aircraft characteristics, such as the reliability of oxygen and pressurisation systems, to the individual tolerance of crew members to pressure changes. As such, a risk management process capable of encompassing all these specificities is required.

The classical methodology for risk management involves mapping the sources of hazard, identifying the causes of each source, determining the consequences associated with each hazard, and establishing mitigation measures for both occurrence and harm. Different types of analyses may be conducted within this process—some more qualitative and subjective in nature, such as the use of risk matrices based on expert opinions employing linguistic variables, and others more quantitative, such as failure modes and effects analysis based on equipment reliability.

In this study, a health risk analysis associated with a high-altitude paratrooper deployment mission was conducted, and a risk sensitivity assessment was performed using Bayesian networks. Specifically, different causal networks were created for three identified risk factors. The probabilities of causal factors and mitigating actions were then updated by integrating new information into the system, and the influence on the probability of the undesired event was assessed.

To present these data, a theoretical introduction to health hazards in high-altitude flight is first provided, followed by an explanation of the principles of event modelling using Bayesian networks. Next, the method adopted for analysing three risk factors present in a high-altitude paratrooper deployment mission is described. Subsequently, the results of the analyses for each risk factor are discussed, concluding with the presentation of the main findings of the study.

2 Risk Management in High-Altitude Free-fall Operations

2.1 Risk Factors

One of the fundamental characteristics of high-altitude paratrooper deployment is the need to depressurise the aircraft in an environment of low temperatures and thin air. In this scenario, both paratroopers and crew members are exposed to the harmful effects of unpressurised flight at altitude, such as decompression sickness and, most notably, hypoxia.

The latter is a condition in which the body's vital systems are impaired due to a deficiency of oxygen, potentially compromising an individual's health and behaviour, and in more severe cases, leading to death. Its effects are typically noticeable in environments with pressure equivalent to altitudes above 10,000 ft [3].

Aeronautical records report at least two fatal incidents resulting from crew hypoxia. In 2005, a Helios Airways Boeing 737-300 suffered a gradual cabin depressurisation, which went unnoticed by the crew, leading to hypoxia among everyone on board [4]. Previously, in 1999, professional golfer Payne Stewart and all crew members aboard a Learjet 35 lost their lives for the same reason, when the aircraft experienced a sudden depressurisation during cruise flight [5].

Decompression sickness results from the formation of inert gas bubbles in body tissues, caused by the reduction in ambient pressure. These bubbles may enter the bloodstream and travel to vital organs or the central nervous system [6]. To minimise its occurrence, protocols are followed in preparation for unpressurised flight, including a mandatory period of breathing pure oxygen prior to depressurisation [7].

Another risk factor associated with the depressurisation process is barotrauma. This term refers to various bodily responses to abrupt changes in altitude, such as tooth pain, middle ear inflammation, sinus pain, intestinal discomfort, and gastric trauma [8]. Specifically regarding otological barotrauma, it is an injury caused by the imbalance between atmospheric pressure and middle ear (ME) pressure, when the pressure changes exceed the tympanic membrane's ability to equalise between the atmosphere and the middle ear [9].

In light of these hazards, missions involving cabin depressurisation at altitude require thorough risk analysis. This analysis identifies the main causes and consequences for each risk factor, as well as mitigation measures to reduce the likelihood and harmful potential of their effects. One methodology used to assess feasible scenarios based on such analysis is the construction of Bayesian networks.

2.2 Bayesian Probability Networks

Bayesian Probability Networks are a graphical representation of events in the form of a directed acyclic graph, in which each node represents an event described by different possible states, either continuous or discrete [10]. The relationship between the nodes is defined through unidirectional edges that indicate the direction of the dependency between them.

The interaction between nodes in the network is established through conditional probabilities, which represent the likelihood of a child node being in a given state, given a set of states of its parent nodes. Nodes without predecessors are considered independent and are assigned unconditional probabilities [10]. These probabilities may be obtained from sources such as failure reports, databases, or expert judgement.

The concept of Bayesian networks is grounded in Bayes' Theorem, which describes the probability of an event given that another event has already occurred, updating beliefs as new evidence becomes available. They are a tool employed in various fields of study involving uncertainty modelling and complex system diagnostics, where the aim is to represent cause-and-effect relationships—one of the key objectives in scenario evaluation within risk analysis.

3 Methods of Analysis

In this study, three Bayesian probability networks were developed, each related to health risk factors associated with high-altitude paratrooper deployment flights. The environment used for development was the Netica software [11].

The steps followed in the construction of each network were:

1. Definition of the causes and effects of the risk factor;
2. Establishment of causal relationships between the nodes;
3. Inclusion of nodes representing risk mitigation measures;
4. Determination of unconditional probabilities; and
5. Determination of conditional probabilities.

Once the network had been constructed, different sensitivity analyses were carried out by updating the state of a node of interest, which altered the final risk value through belief updating.

It is worth noting that the probabilities used in this study were derived from the authors' judgement, based on their experience in aeronautical operations.

4 Results

4.1 Hypoxia

Figure 1 illustrates the Bayesian probability network proposed for assessing the causes that could lead to the occurrence of hypoxia and its consequences during high-altitude paratrooper deployment.

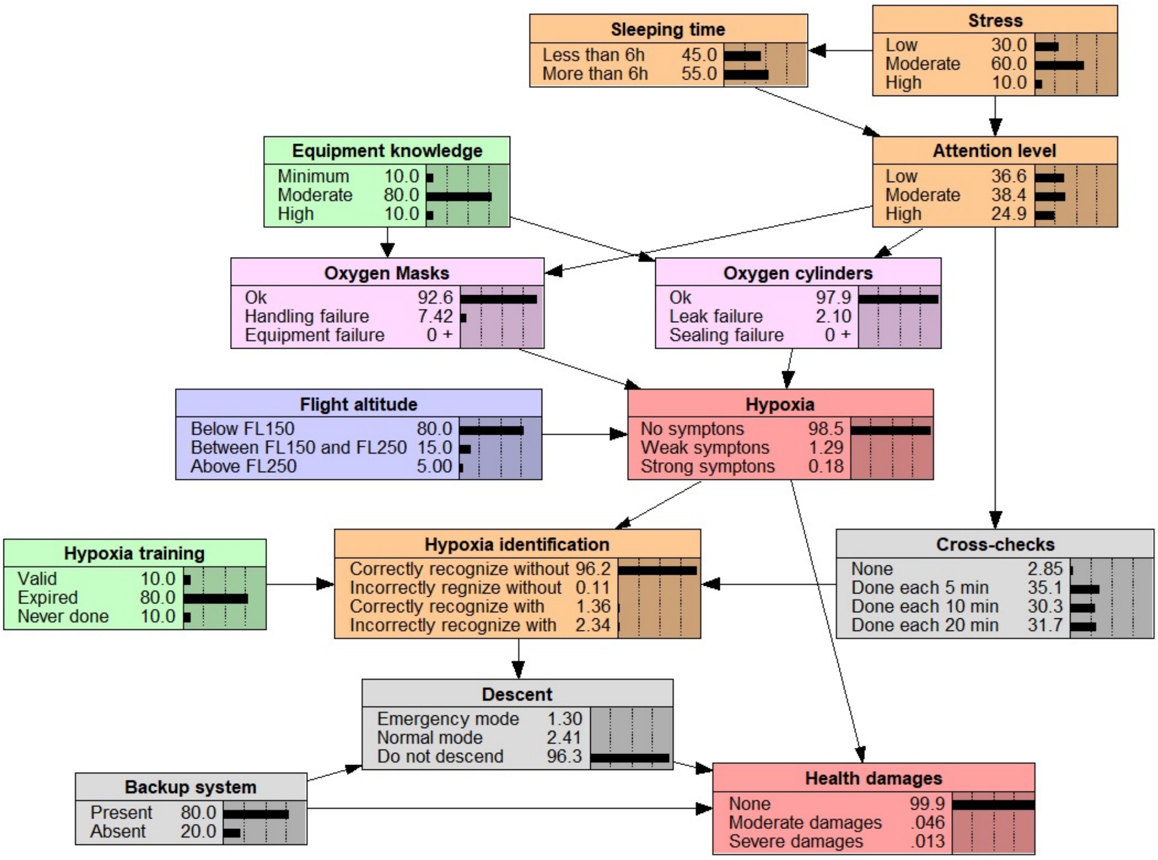

Figure 1: Bayesian Probability Network for Hypoxia during High-Altitude Paratrooper Deployment Flights.

In red are the nodes related to the effects that should be avoided during the flight, which for this analysis are hypoxia and health damage to a member of the team. In orange are the nodes associated with individual factors, such as pre-flight rest and attentiveness during the flight, and most importantly, the ability of the crew member or paratrooper to correctly recognise that they are experiencing symptoms of hypoxia. This last factor is decisive in the individual's judgement to activate or not the post-hypoxia risk mitigation procedures, which directly influence the ultimate consequence of someone on board suffering health damage.

In pink are the nodes related to oxygen system equipment and its possible modes of operation. The analysis did not aim to exhaust all material failure modes, given that the probability of equipment failure is considered very low due to the strict certification standards these systems must meet. Therefore, operational failures were broadly defined to include any negative events related to improper handling of oxygen masks, including maintenance errors. Since this type of flight requires additional oxygen cylinders and potential pressure line connections, the possibility of oxygen leaks was also included.

In blue is the node relating to the environmental conditions under which the flight takes place. This has a direct impact on the severity of hypoxia symptoms due to the reduction in useful consciousness time and partial oxygen pressure at increasing altitudes. In green are the nodes related to individual preparedness of mission participants. In this regard, hypoxia training, usually conducted in hypobaric chambers or using controlled oxygen-volume systems, is a preventative risk mitigation measure applied prior to symptom onset.

In grey are the mitigation procedures both before and after the onset of hypoxia, mainly aimed at reducing the severity of in-flight health effects. These include the presence of backup breathing systems in the event of main system failure and the execution (or not) of a descent to a safe altitude that allows breathing without masks, either under normal or emergency conditions. Also included is the possibility for crew members to carry out routine equipment and consciousness checks at fixed intervals during the flight to quickly detect anomalies.

For the proposed model, the estimated risk of a participant experiencing moderate health effects, including severe headache, fainting, hyperventilation, nausea, and prolonged visual impairment, is approximately 1 in 2,000 flights. The risk of severe outcomes, such as death or irreversible brain damage, is around 1 in 10,000 flights. But, if the flights occur knowingly at altitudes above 25,000 ft, the risk of moderate effects increases to nearly 3 in 1,000 flights, and the risk of severe effects to approximately 1 in 1,000, as shown in Figure 2.

From the comparison of Figures 3 to 5, assessing the individual's ability to recognise hypoxia above 25,000 ft, the risks of moderate and severe effects for someone with expired training increase almost threefold compared to someone with current training. Compared to an individual who has never undergone training, these risks increase by up to eightfold.

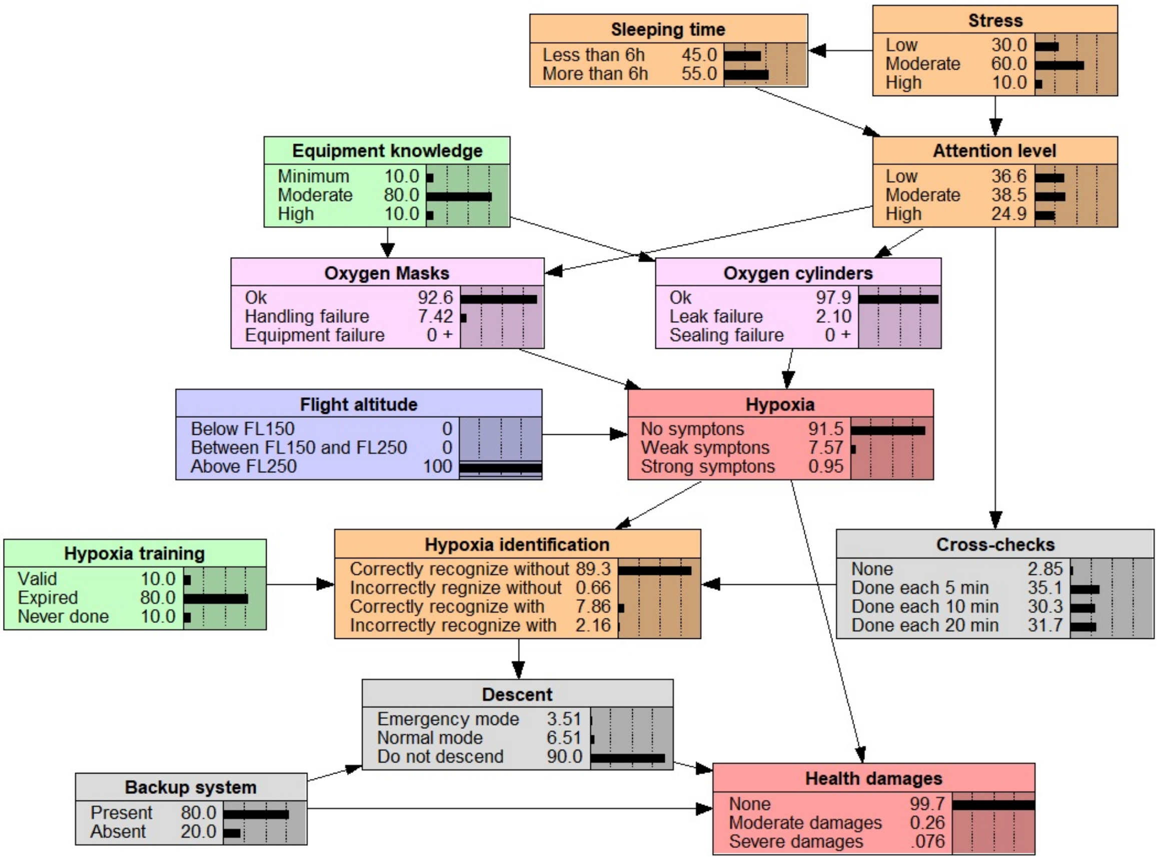

Figure 2: Bayesian Probability Network for Hypoxia in Paratrooper Deployment Flights Above 25,000 ft.

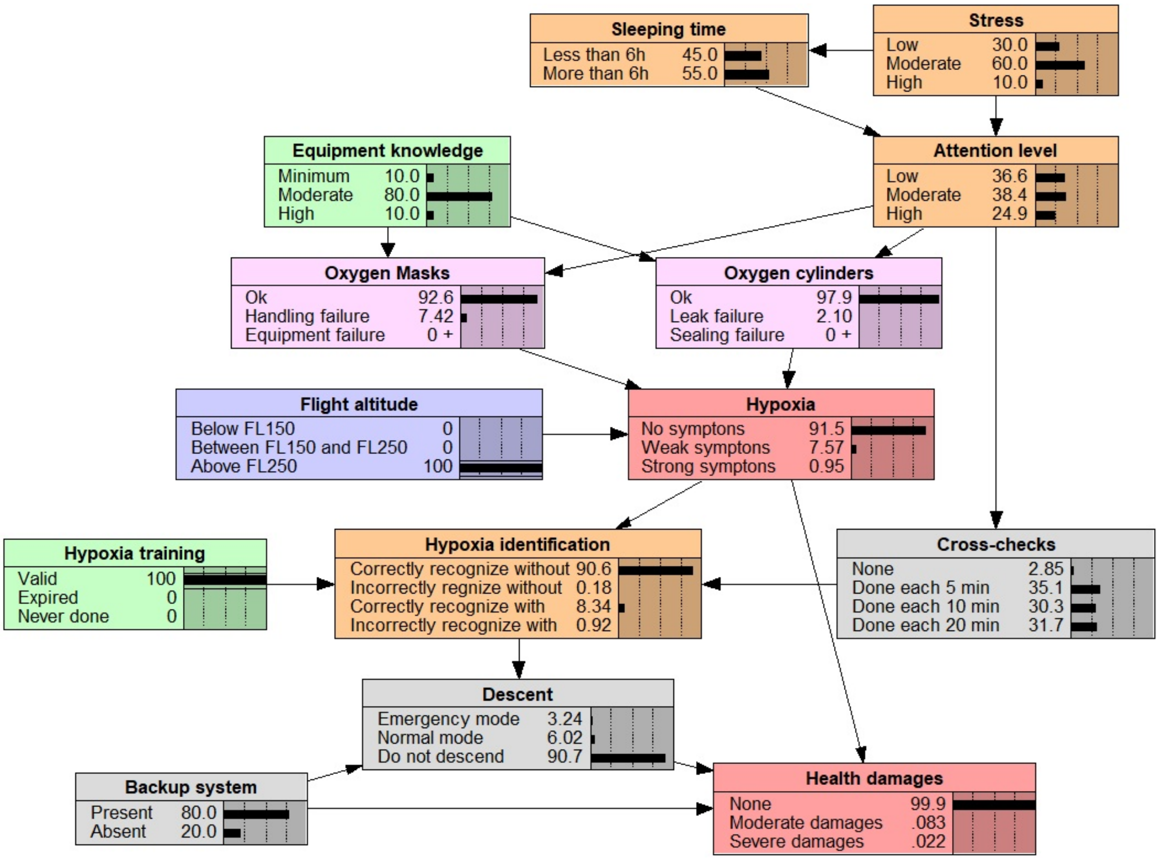

Figure 3: Bayesian Probability Network for Hypoxia in Paratrooper Deployment Flights Above 25,000 ft with Valid Hypoxia Training.

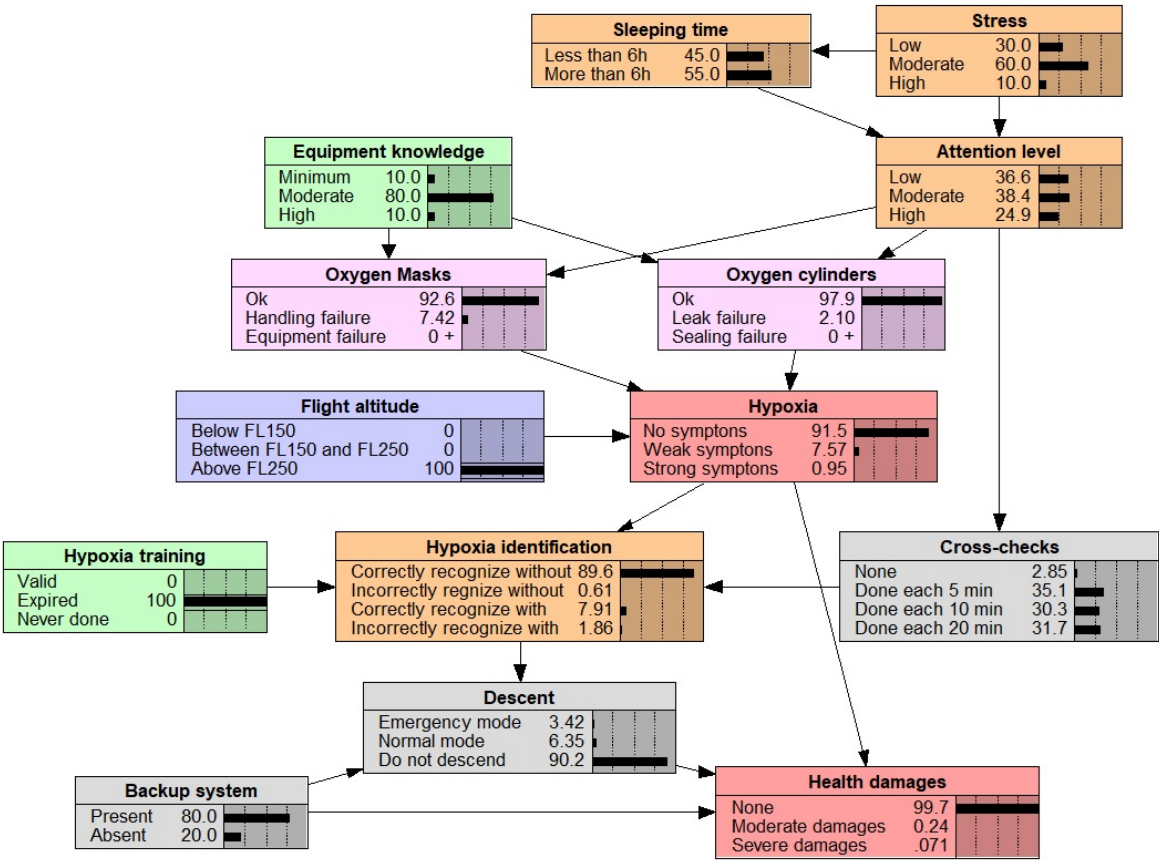

Figure 4: Bayesian Probability Network for Hypoxia in Paratrooper Deployment Flights Above 25,000 ft with Expired Hypoxia Training.

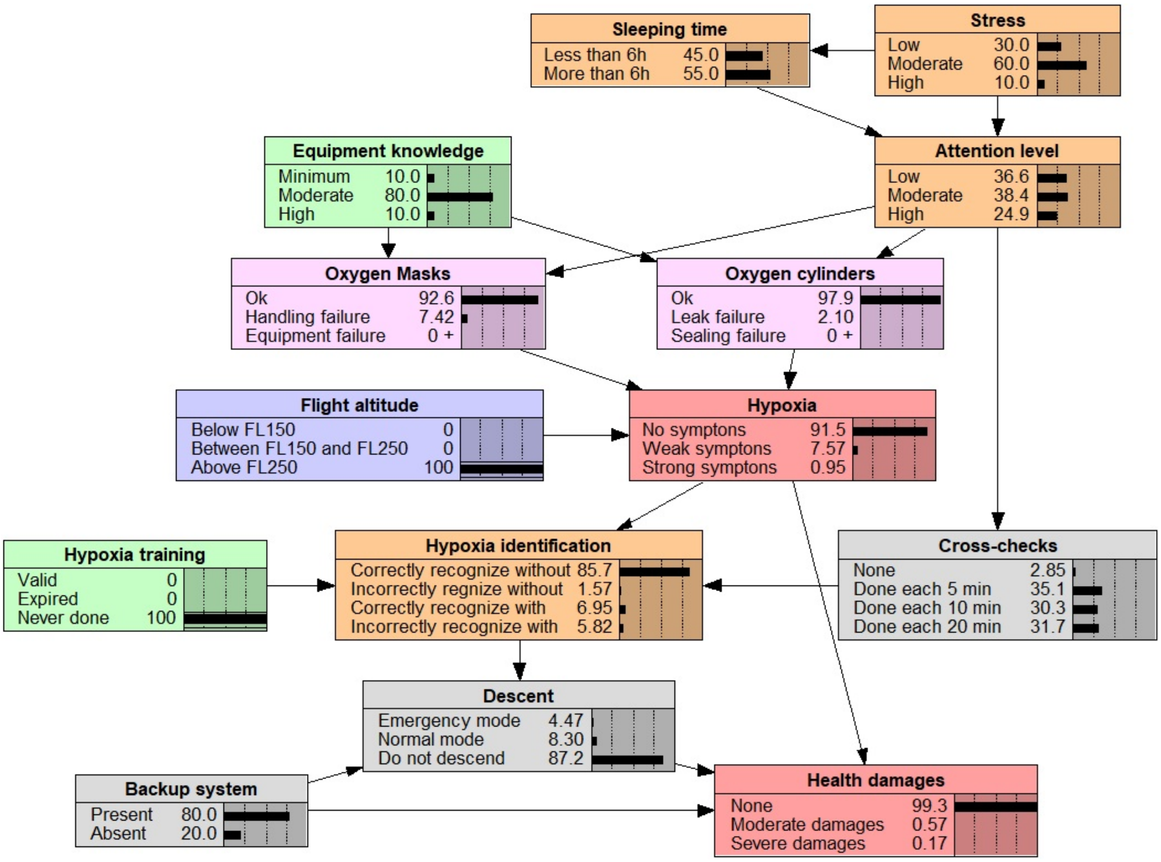

Figure 5: Bayesian Probability Network for Hypoxia in Paratrooper Deployment Flights Above 25,000 ft Without Hypoxia Training.

Therefore, within this model, training crew members and paratroopers to recognise hypoxia proves to be highly desirable for minimising risks during high-altitude paratrooper deployment flights.

4.2 Decompression Sickness

Figure 6 illustrates the Bayesian probability network proposed for assessing the causes that could lead to the occurrence of decompression sickness and its consequences during high-altitude paratrooper deployment flights.

The colour scheme used for the nodes in this network is the same as in the previous section. According to the proposed model, the risk of any crew member or paratrooper suffering severe harm from decompression sickness—such as severe embolism, aneurysm, or death—is practically negligible. Moderate effects, such as intense itching, skin irritation, or joint pain, are estimated to occur at a rate of approximately 1 in 50,000 flights.

The main causes of decompression sickness following unpressurised high-altitude flight are insufficient elimination of inert gases from the bloodstream and abrupt pressure variations within the cabin. The first cause is mitigated by a process of blood denitrogenation, achieved by breathing pure oxygen for a prescribed period, depending on the flight level at which the aircraft is to remain unpressurised for an extended duration. The second cause is mitigated through proper control of the rate of pressure reduction in the cabin until it matches the external atmospheric pressure at the flight level—essentially, raising the internal cabin altitude to match the aircraft's flight altitude.

The minimum time required for breathing 100% oxygen at full partial pressure is provided in Table 1 [7]. This procedure is typically conducted on the ground, but it may also be performed in flight up to an altitude of 16,000 ft. If interrupted at any point, the countdown must be restarted from zero.

Table 1: Minimum Denitrogenation Time with 100% Oxygen at Full Partial Pressure.

Cabin Altitude (ft)	100% O_2 Time (minutes)
Up to 18,000	None
18,000 to 25,000	30
25,000 to 30,000	45
30,000 to 35,000	60
Above 35,000	75

Assuming the minimum denitrogenation time is respected, events that could lead to inadequate elimination of nitrogen from the bloodstream are primarily associated with improper

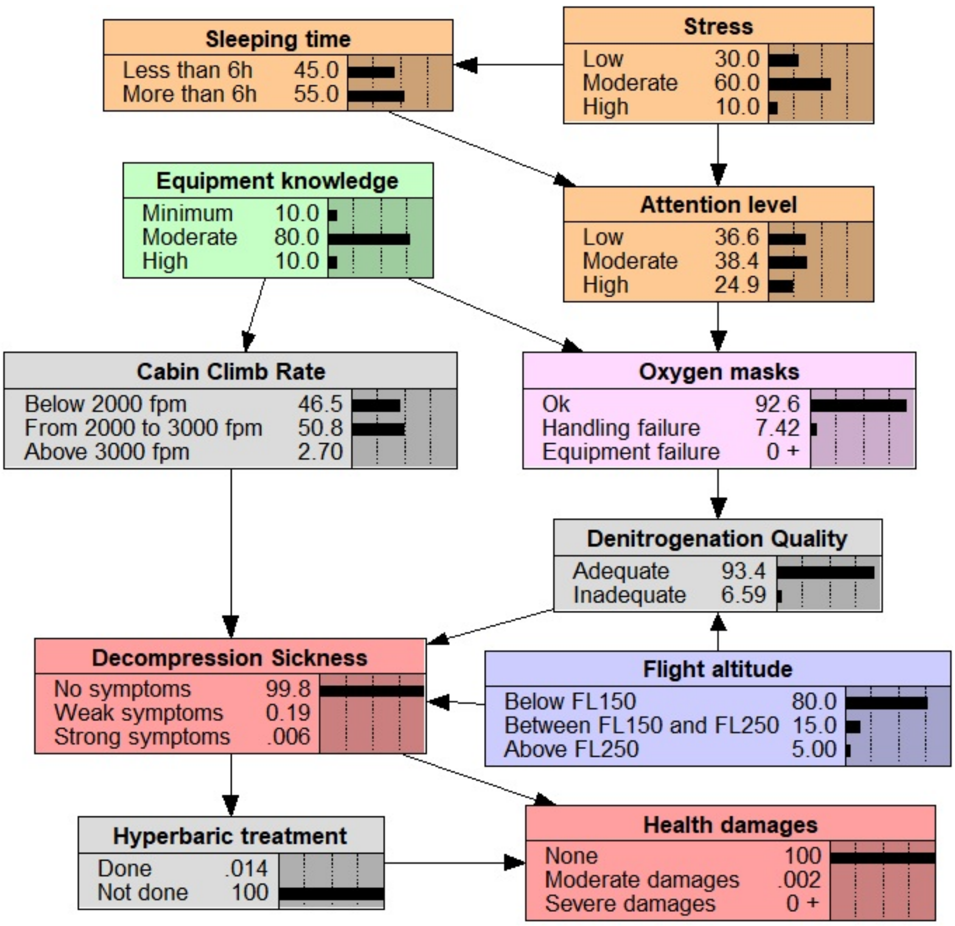

Figure 6: Bayesian Probability Network for Decompression Sickness in High-Altitude Paratrooper Deployment Flights.

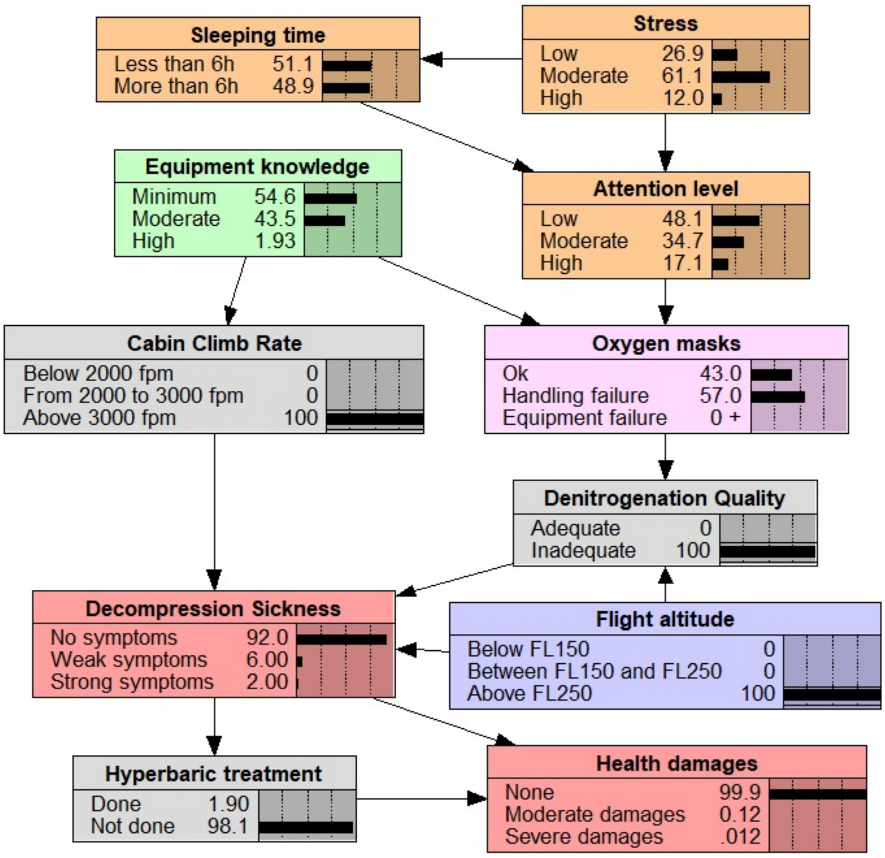

Figure 7: Bayesian Network for Decompression Sickness in Paratrooper Deployment Flights Above 25,000 ft, with Inadequate Denitrogenation and Cabin Ascent Rate Greater Than 3,000 fpm.

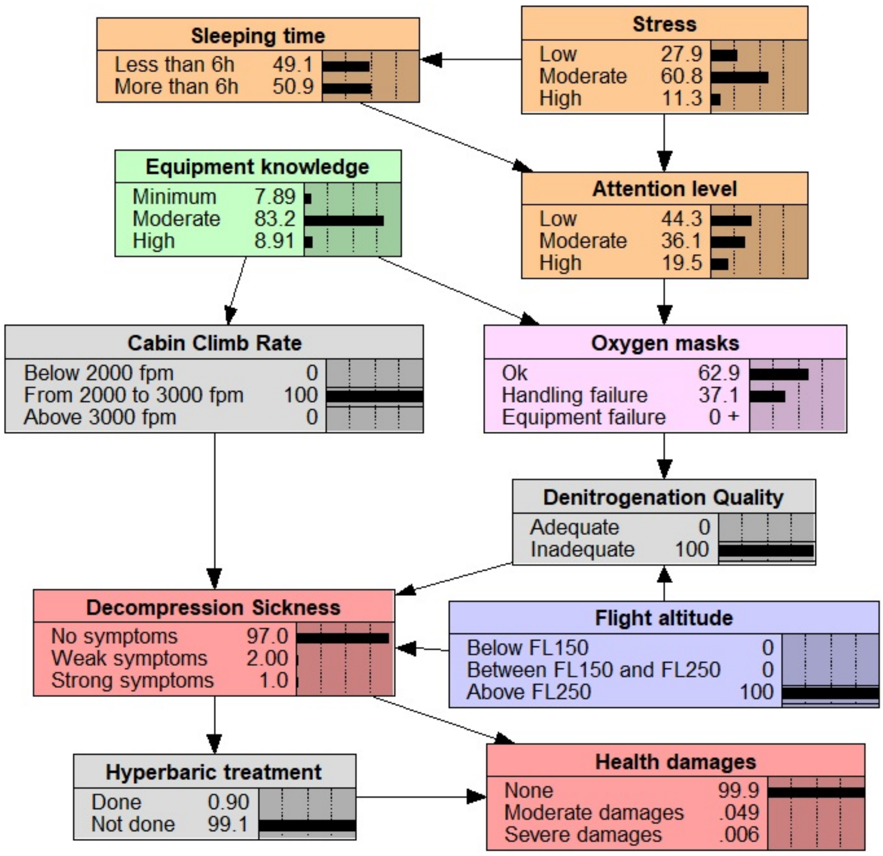

Figure 8: Bayesian Network for Decompression Sickness in Paratrooper Deployment Flights Above 25,000 ft, with Inadequate Denitrogenation and Cabin Ascent Rate Between 2,000 and 3,000 fpm.

operation of the oxygen masks—particularly due to poor fit on the face. These events were modelled as part of the possible operational failures of the masks. The cabin ascent rate was divided into three possible intervals, based on an aircraft equipped with a system capable of controlling the rate of pressure change.

As a mitigation measure following the onset of any symptoms of decompression sickness, the use of treatment in a specialised hyperbaric chamber was considered. In this treatment, the body is subjected to increased pressure in order to enhance the solubility of gases in the bloodstream.

According to the proposed model, in extreme cases—such as inadequate denitrogenation combined with a cabin ascent rate greater than 3,000 fpm during a flight conducted above 25,000 ft—the risk of moderate health effects is approximately 1 in 1,000 flights, while the risk of severe effects is nearly 1 in 100,000 flights. By controlling the ascent rate alone, and limiting it to between 2,000 and 3,000 fpm, the risks are reduced by almost half, as shown in Figures 7 and 8.

In general, within the constructed model, decompression sickness may be considered a risk factor with less health impact compared to hypoxia, for example. Such information can be useful in mission planning—particularly when determining whether further mitigation measures are necessary, and in prioritising efforts towards mitigating the most significant risk factors in terms of both probability and severity.

4.3 Barotrauma

Figure 9 illustrates the Bayesian probability network proposed for assessing the causes that could lead to the occurrence of otological barotrauma and its consequences during high-altitude paratrooper deployment flights.

The colour scheme used for the nodes in this network is the same as in the previous cases. According to the proposed model, the risk of a flight participant experiencing moderate damage due to otological barotrauma is 1 in 250 flights. These effects include temporary hearing loss and moderate ear pain. The risk of severe damage to a crew member is approximately 3 in 5,000 flights, which could include acute ear pain, rupture of the tympanic membrane, and hearing loss.

A key contributing factor to the occurrence of barotrauma is abrupt pressure variation, such as those resulting from changes in internal cabin altitude. Factors identified as influencing this rate of pressure change include the availability of onboard oxygen, which may compel pilots to descend more rapidly, and the type of descent executed, depending on whether an onboard emergency demands an urgent descent.

Flight altitude also influences both descent time and the overall pressure variation to which crew and paratroopers are exposed. One mitigation measure following the occurrence of symptoms is staged descent, with intermittent level-offs to allow relief of symptoms for the affected individual.

Another factor that directly affects both the probability and severity of otological barotrauma is the degree of upper airway congestion in the individual. The body needs to balance the pressure between the atmosphere and the middle ear, often using techniques such as the Valsalva manoeuvre. However, if the airways are congested, this equalisation becomes difficult or even impossible, depending on the severity of the blockage. Consequently, barotrauma symptoms worsen as the pressure differential increases.

According to the model, individual health status, particularly airway congestion, is the most influential factor in increasing the probability of health-related damage during flight, as illustrated in Figures 10 to 12. For unpressurised flights above 25,000 ft, with cabin altitude change rates limited to between 2,000 and 3,000 fpm, the risk of moderate barotrauma is 1 in 200 flights when all members have clear upper airways, and the risk of severe damage is 1 in 2,000 flights.

If there is a moderate level of airway congestion, the risk of moderate damage increases to 1 in 33 flights, and the risk of severe damage to 1 in 200 flights. With severe airway congestion, these risks rise to approximately 1 in 15 flights and 1 in 66 flights, respectively.

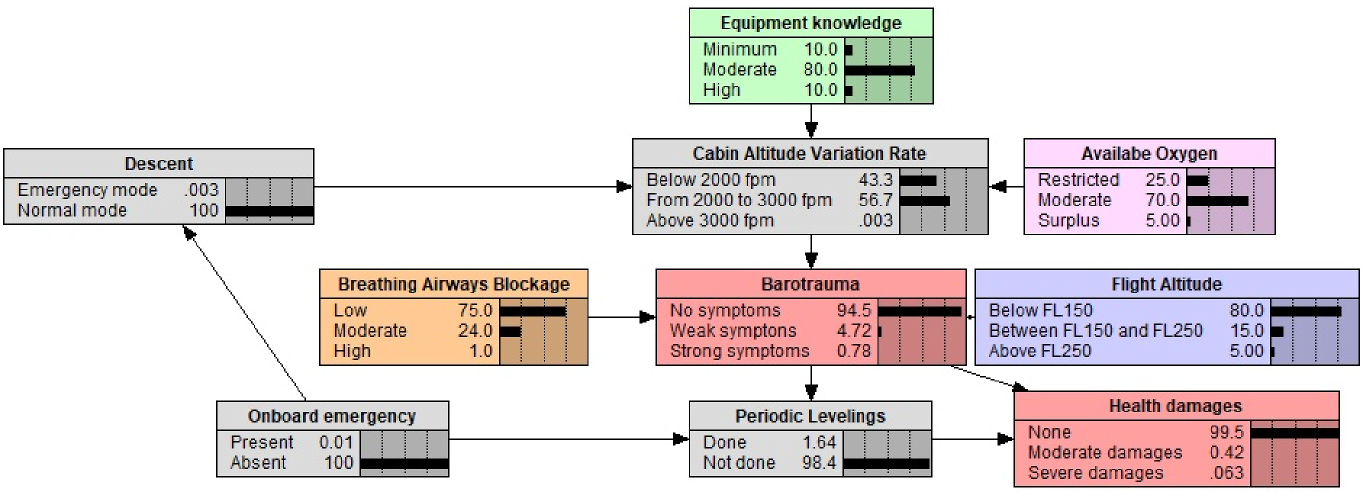

Figure 9: Bayesian Probability Network for Otological Barotrauma in High-Altitude Paratrooper Deployment Flights.

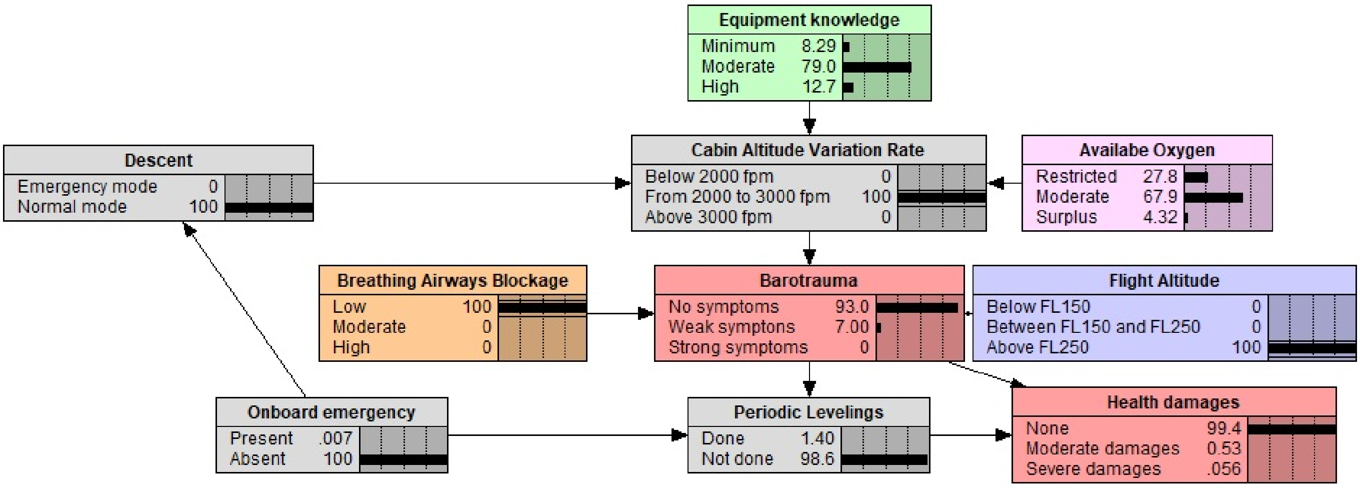

Figure 10: Bayesian Probability Network for Otological Barotrauma in Paratrooper Deployment Flights Above 25,000 ft, with Cabin Altitude Change Rate Between 2,000 and 3,000 fpm and Low Airway Congestion.

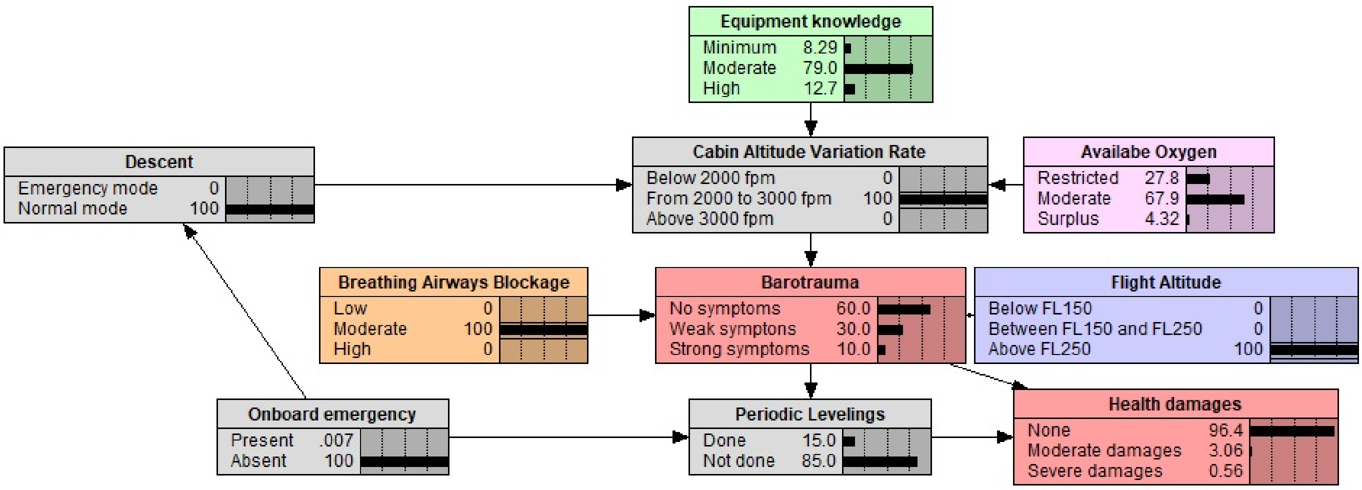

Figure 11: Bayesian Probability Network for Otological Barotrauma in Paratrooper Deployment Flights Above 25,000 ft, with Cabin Altitude Change Rate Between 2,000 and 3,000 fpm and Moderate Airway Congestion.

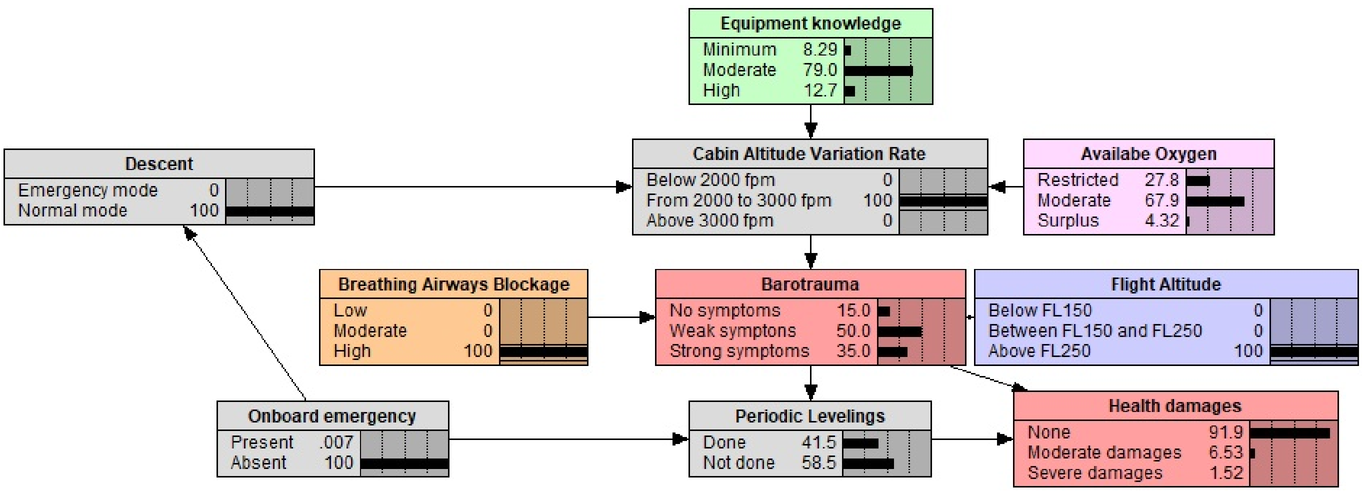

Figure 12: Bayesian Probability Network for Otological Barotrauma in Paratrooper Deployment Flights Above 25,000 ft, with Cabin Altitude Change Rate Between 2,000 and 3,000 fpm and Severe Airway Congestion.

5 Conclusions

For the three health hazards in high-altitude paratrooper deployment missions discussed in this study, different causal factors were identified for each, and various risk mitigation measures were proposed. In this context, the application of Bayesian probability networks made it possible to relate these elements within a common occurrence scenario both graphically and mathematically. Moreover, it enabled the direct analysis of the impact of conditional dependencies between them on the likelihood of harm to mission participants. From these studies, the most influential elements in both occurrence and prevention were identified, demonstrating the method's potential as a support tool for mission planning through scenario simulation.

It is important to note that the models presented do not aim to exhaust all possible interactions that may lead to any of the three risk factors discussed, nor to cover the entire range of possible risk mitigation actions. However, they provide a reference framework for more detailed planning. Given that the mission may be carried out using different aircraft and various operational equipment configurations, the types of probabilities and their corresponding values should be treated as indicative and require further refinement according to the specificities of each project.

With these considerations in mind, the analysis revealed that hypoxia and otological barotrauma were the most significant risk factors in high-altitude paratrooper deployment missions, based on the constructed networks. In contrast, decompression sickness presented a lower probability of occurrence and severity in comparison. For the first two events, the human factor proved highly influential in determining mission risk. Although the risk of decompression sickness is also affected indirectly by human behaviour, it was more closely related to procedural aspects during flight—such as control of the cabin ascent rate.

In the case of hypoxia, the importance of the human factor was reflected in the individual's ability to correctly recognise their oxygenation state, highlighting the importance of conducting hypoxia training prior to the mission. For barotrauma, the individual's upper airway condition, specifically the absence of obstructions, was a key determinant in their ability to equalise internal ear pressure with the atmospheric pressure.

To further enhance the models developed, future studies should focus more closely on defining the probabilities associated with each proposed event, using a greater volume of historical data and consulting a broader range of experts. Additionally, a valuable area for future research would be the development of Bayesian probability networks that incorporate logistical, maintenance, and operational factors of the mission. Such models would allow the identification of key success factors and improve the situational awareness of those involved—enhancing not only safety, the focus of this study, but also operational readiness for future missions.

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