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Original Research Paper

Cardiovascular

STRUCTURED COMPREHENSIVE MODEL GENERATION USING AI FOR PREDICTION OF MICROBUBBLE FORMATION DURING EXTRAVEHICULAR ACTIVITIES IN ASTRONAUTS.

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ABSTRACT Creation of a structured comprehensive model using AI for prediction of risk of microbubble formation during extravehicular activities in astronauts. Building a comprehensive AI model to analyse microbubble formation in decompression sickness (DCS) among astronauts involves multiple interdisciplinary components. Here is a step-by-step approach to structure such a model. Adding bubble formation, flow choking, and shockwave generation evaluation using microfluidic channel experiments can provide controlled, detailed insights into decompression sickness (DCS) and microbubble dynamics under space-relevant conditions. Microfluidic channels allow for fine-grained control of flow, pressure, temperature, and gas saturation, which helps simulate the exact conditions that might be encountered during extravehicular activities (EVAs) on Mars and the Moon.

KEYWORDS : DCS -Decompression sickness, EVA- Extravehicular Activity, AI-Artificial Intelligence

INTRODUCTION

With the expansion of human space exploration to Mars and lunar missions, understanding and managing the risks associated with decompression sickness (DCS) has become crucial. DCS occurs when dissolved gases in the body form bubbles due to rapid pressure changes, posing significant health threats during extravehicular activities or habitat depressurizations in space environments. AI modelling offers a powerful tool for predicting DCS by analysing complex physiological and environmental variables. By using machine learning algorithms trained on historical data and physiological markers, AI can provide more accurate, individualized risk assessments, enabling safer mission planning and real-time decision-making. As space missions venture further from Earth, predictive AI modelling becomes invaluable in mitigating the health risks associated with deep-space exploration.

METHODOLOGY

1. Defining Objectives and Key Parameters

Primary Objective: Predict the formation, dynamics, and potential impacts of microbubbles in the bloodstream due to decompression under microgravity conditions.

Key Output Variables:

o Risk of DCS based on environmental and individual factors.

o Bubble formation and characteristics: size, stability, growth rate.

o Flow and behaviour of bubbles in bloodstream under varied conditions (microgravity, radiation exposure).

2. Model Structure

To tackle the multifaceted nature of this problem, the AI model would need to be structured in modules, with each module simulating and feeding data into the next. These modules could include:

Module 1: Microgravity Flow Dynamics

Purpose: Simulate the altered blood flow dynamics in microgravity.

Inputs: Hemodynamic parameters such as heart rate, blood flow velocity, and vessel diameter.

Outputs: Predicted changes in blood flow patterns and bubble distribution due to lack of gravity.

Module 2: Bubble Nucleation and Growth

Purpose: Model nucleation sites and growth characteristics of microbubbles.

Key Variables:

o Bubble Size Distribution: Distribution and size evolution over time.

o Membrane Interactions: Effects of cell membrane properties and bubble adhesion.

o Shockwave Generation: Assess shockwaves generated by expanding bubbles and their impact on adjacent cells.

Physics Considerations:

o Rayleigh–Plesset Equation: To simulate the dynamics of bubble growth in response to pressure changes.

o Bubble Heat Transfer: Influence of the blood's heat capacity ratio on bubble stability.

Module 3: Blood Rheology and Membrane Properties

Purpose: Account for the fluid dynamics properties of blood and its interaction with bubbles.

Inputs:

o Blood Viscosity: Altered by factors like radiation and genetic predispositions.

o Membrane Properties: Flexibility, surface tension, and permeability of cell membranes (influenced by genetic factors).

Outputs: Interaction outcomes between bubbles and blood cells, such as clotting risks and bubble entrapment.

Module 4: Physiological and Environmental Factors

Purpose: Integrate genetic and environmental influences on bubble formation and DCS risk.

Factors Included:

o Genetics: Variation in individual predispositions to bubble formation.

o Radiation Exposure: Effects on blood properties and cellular structures.

o Pre-breathing Protocols: Influence of oxygenation levels in reducing initial nitrogen levels and bubble nucleation sites.

Machine Learning (ML) Models: Use predictive models like neural networks or ensemble methods trained on astronaut

health data (if available) or simulated data for prediction of genetic and environmental impacts on DCS likelihood.

3. Data Requirements and Sources
Simulated Microgravity Flow Data: From experiments or computational fluid dynamics (CFD) simulations mimicking microgravity.
Historical Astronaut Health Data: For understanding predispositions and DCS cases in space.
Genetic Data on DCS Susceptibility: Genetic markers linked to DCS risk.
Environmental Impact Data: Radiation exposure effects on blood and tissues.
Pre-breathing Protocol Effectiveness: Data from hyperbaric or space simulation studies.

4. Model Integration and Execution
Flow Simulation (CFD): Use computational fluid dynamics (CFD) to simulate blood flow and bubble dynamics in microgravity.

Machine Learning Pipeline:
o Feature Engineering: Incorporate variables from the flow, bubble, and physiological data.
o Model Training: Supervised learning on historical astronaut health and decompression data to predict DCS occurrence.
o Model Testing & Validation: Simulated test environments for robustness and validation.

5. Outputs and Predictions
Real-Time Risk Score: A probability score for DCS based on real-time biometrics.
Bubble Characteristics Visualization: Size and distribution of bubbles under varied conditions.
Simulation of Shockwave and Heat Transfer Effects: Expected shockwave impacts on blood cells and heat dissipation effects.

6. Further Extensions and Optimizations
Simulation of Emergency Interventions: Model emergency protocols for DCS mitigation.

Adaptive Learning: The model could continuously update and refine predictions with additional data on astronaut responses to decompression.
1. Defining Environmental Differences in Mars and Lunar EVAs
Mars:
o Gravity: Approximately 0.38g (38% of Earth's gravity).
o Atmosphere: Primarily CO_2, very thin, requiring full pressurization.
o Radiation: Higher exposure than Earth, though somewhat shielded by Mars's thin atmosphere.
o Temperature Variability: Extreme, from -140°C to 30°C.

Moon:
o Gravity: Approximately 0.16g (16% of Earth's gravity).
o Atmosphere: Nearly non-existent; requires full pressurization.
o Radiation: Very high; no atmospheric or magnetic protection.
o Temperature Variability: More extreme, from -173°C to 127°C depending on exposure to sunlight.

Each of these conditions can affect both the human physiology and the bubble dynamics, and they inform the selection of parameters for each module.

2. Expanded Model Modules and Parameters
Module 1: Altered Flow Dynamics under Reduced Gravity (Mars and Lunar Conditions)
Objective: Simulate blood flow changes due to lower gravity on Mars and the Moon.

Additional Parameters:
o Gravity Level: Modify blood flow rates and pressure dynamics based on gravitational differences (e.g., lower blood pressure in lower gravity environments).
o Suit Design and Restrictions: Incorporate pressurization and movement restriction effects from spacesuits, impacting hemodynamics.
o Temperature Fluctuations: Adjust flow dynamics for extreme external temperatures and their effect on body core and extremity blood flow.

Outputs:
o Flow patterns under altered gravity (Mars/Moon).
o Temperature-adjusted flow in response to environmental shifts.

Module 2: Bubble Nucleation, Growth, and Behaviour
Purpose: Model bubble behaviour with temperature, shockwave, and pressure gradients specific to Martian and lunar EVA conditions.

New Parameters:
o Temperature Variations: Integrate external temperature changes and their effects on the gas solubility in blood, which influences bubble nucleation and growth.
o Bubble Stability in Reduced Gravity: Simulate bubble expansion under reduced gravity using adapted Rayleigh–Plesset and Navier–Stokes equations.
o Shockwave Dynamics: Altered shockwave impact due to bubble expansion or collapse with less gravitational pull; effects may be weaker but could propagate differently.

Outputs:
o Dynamic bubble formation model showing nucleation under Mars and Moon conditions.
o Predictive bubble stability for EVAs.

Module 3: Physiological and Environmental Factors for DCS in Space Environments
Objective: Account for EVA-specific risks for DCS in the unique environments of Mars and the Moon.

Expanded Factors:
o Pre-breathing Protocol Variability: Assess the efficacy of oxygenation protocols used prior to EVAs in different atmospheric pressures and gravity levels.
o Radiation Impact on Blood and Tissues: Model additional oxidative stress and cellular damage due to heightened radiation exposure.
o Genetic Risk Factors: Account for possible increased DCS susceptibility due to genetic variations that may be exacerbated by Martian or lunar conditions.
o Blood Viscosity and Cellular Adaptations: Monitor blood viscosity changes with prolonged exposure to microgravity during transit, which could impact DCS risk during Mars or Moon landings.

Machine Learning Integrations:
o Predictive Models for Individual DCS Risk: Train models on simulated EVA data, factoring in genetic predispositions, radiation exposure, and oxygenation levels to predict individual risk under Mars and Moon conditions.

Module 4: Extravehicular Suit Pressurization Effects on Bubble Dynamics
Purpose: Assess the effects of spacesuit pressurization and decompression cycles on blood bubble formation.

Additional Parameters:
o Suit Pressurization Levels: Integrate standard suit

pressurization and decompression rates used in Mars and lunar EVAs.
o Pressurization Cycles for Mars EVAs: Include simulation of pressurization cycles for Mars EVAs (different than those required for the Moon).
o Environmental Suit Conditioning: Add thermal and metabolic constraints from EVA suits.

Output:
o Bubble formation likelihood model based on decompression and suit pressurization cycles.

3. Data Requirements for Mars and Lunar EVAs
· Simulated EVA Blood Flow Data: Computational models or data from analog missions simulating Martian and lunar gravity.
· Spacesuit Design Data: Data on pressure cycles, thermal characteristics, and metabolic load restrictions of EVA suits.
· Mars and Lunar Radiation Models: Predictive radiation exposure data under Martian and lunar conditions.
· Temperature-Dependent Solubility Models: Data on gas solubility in blood under variable temperatures for Mars and Moon.

4. Integration of Mars and Lunar Conditions into AI Model
· Blood Flow Dynamics Module: Integrate simulated data to reflect blood flow under Mars and Moon gravity, temperature, and pressurization.
· Bubble Nucleation and Dynamics: Adapt bubble models to consider temperature and pressure impacts unique to Mars and Moon EVAs.
· Risk Prediction Module: Use machine learning to develop predictive risk scores for DCS during Mars and Moon EVAs, including variables for genetic predisposition, radiation exposure, and oxygenation efficiency.

5. Outputs and Visualizations
· Predictive EVA Suit Pressurization Risk Map: A risk map for DCS during Martian and lunar EVAs, considering suit pressures and decompression schedules.
· Real-Time DCS Monitoring: Predictive alerts for DCS based on real-time biometrics.
· Bubble Formation Visualization: Real-time visualization of bubble size, distribution, and movement within the bloodstream under Mars/Moon gravity conditions.
· Temperature-Adjusted Flow and Shockwave Visualization: Simulated visualizations showing blood flow, bubble behaviour, and shockwave effects under extreme temperature changes.

1. Bubble Nucleation and Growth Models
Bubble nucleation, growth, and stability are influenced by temperature, pressure, and gravity. Here's how we can structure these calculations:
1.1 Bubble Nucleation Modelling
Nucleation Theory: The classical nucleation theory (CNT) is often used to model bubble formation, where gas nuclei form in blood due to supersaturation after decompression.

$$r_{crit} = \frac{2\gamma}{\Delta P}$$

where:

- γ = Surface tension of blood (modified by factors like microgravity).
- ΔP = Pressure difference (external pressure vs. blood pressure).

o Critical Radius (r_crit): The size above which a bubble is more likely to grow rather than dissolve.

o Nucleation Rate (J):

$$J = A \exp\left(-\frac{\Delta G}{k_B T}\right)$$

where:

- A = Pre-exponential factor related to molecular collision frequency.
- ΔG = Energy barrier for nucleation, influenced by gravity, pressure, and temperature.
- k_B = Boltzmann constant.
- T = Temperature, adjusted for Martian or lunar EVA conditions.

The rate of new bubble formation per unit volume. Enhanced Nucleation in Microgravity: Under reduced gravity (Mars and Moon), surface tension and buoyancy effects change, impacting the critical radius and nucleation rate. Microgravity conditions lower the effectiveness of buoyancy-driven bubble clearance, meaning bubbles are more likely to persist.

1.2 Bubble Growth Dynamics

Rayleigh–Plesset Equation: This equation models the radial dynamics of a bubble in a fluid under pressure variations, accounting for bubble expansion and collapse:

$$R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{1}{\rho}\left(P_g - P_0 - 4\frac{\mu}{R}\frac{dR}{dt} - \frac{2\gamma}{R}\right)$$

where:

- R = Radius of the bubble.
- ρ = Blood density.
- P_g = Gas pressure inside the bubble.
- P_0 = Ambient blood pressure.
- μ = Blood viscosity.
- γ = Surface tension of the blood.

Gas Solubility Adjustments: Factors like external temperature fluctuations (extreme cold on the Moon or variable on Mars) alter gas solubility in blood, impacting the growth or shrinkage of bubbles.

o Henry's Law Constant: Adjusted for different temperatures to estimate dissolved gas concentration, with colder conditions reducing solubility, which may increase free gas (bubbles).

Temperature and Shockwave Impacts: Temperature swings may cause thermal expansion or contraction of bubbles, affecting stability and introducing shockwaves. This would be modelled by:

$$dV = \alpha V dT$$

where:

- dV = Change in bubble volume.
- α = Thermal expansion coefficient.
- dT = Temperature change.

2. Radiation Effects On Blood And Cellular Structures

Radiation exposure on Mars and the Moon is high, affecting blood properties, cellular integrity, and potentially increasing susceptibility to DCS.

2.1 Modelling Radiation-induced Cellular Damage

Types of Radiation:
o Galactic Cosmic Rays (GCR): High-energy particles that can damage cellular DNA and increase oxidative stress.
o Solar Particle Events (SPEs): High doses of protons that lead to acute radiation damage.

DNA Damage and Oxidative Stress modelling:
o Direct Damage: Radiation-induced breaks in DNA strands (single and double-strand breaks) can lead to cellular apoptosis or mutations.

o Indirect Damage: Radiation increases reactive oxygen species (ROS) in cells, which leads to oxidative stress and impacts blood viscosity and cellular adhesion.

Mathematical modelling of Damage:
o Linear-Quadratic (LQ) Model: Often used for modelling dose-response relationships in radiation biology.

$$D_{cell} = \alpha D + \beta D^2$$

where:

- D_{cell} = Cellular damage (e.g., strand breaks).
- D = Radiation dose.
- α and β are constants that depend on radiation type and cell sensitivity.

Impact on Blood Viscosity and Clotting:
o Radiation-induced cellular damage leads to higher blood viscosity due to increased cellular debris and inflammatory response.
o Blood Viscosity (\eta): Modelled as a function of haematocrit and plasma protein levels, which are impacted by radiation-induced stress responses.

2.2 Radiation Effects on Bubble Nucleation
Increase in Gas Micro-Nucleation Sites: Cellular damage and oxidative stress can increase micro-nucleation sites due to cell membrane changes and elevated plasma proteins.

Increased Susceptibility to DCS: Cells with damaged membranes may be more prone to forming bubbles due to altered membrane permeability and reduced surface tension stability.

2.3 Radiation Adaptation in Machine Learning Models
Predictive modelling:
o Input Variables: Radiation dose (GCR, SPE), haematocrit levels, viscosity, oxidative stress markers, pre-EVA conditions.
o Outputs: Adjusted risk scores for DCS based on cumulative radiation exposure and physiological changes.
o Modelling Technique: A deep neural network or an ensemble model could be trained on historical spaceflight and radiation exposure data to predict the cumulative effect of radiation on DCS risk.

3. Integrating Modules for Mars and Moon EVA Conditions
1. Flow Simulation (CFD):
o Incorporate Rayleigh–Plesset and temperature fluctuation equations.
oSimulate flow dynamics under reduced gravity with varying bubble stability and growth rates based on temperature, radiation, and pressure factors.

2. Machine Learning Pipeline:
o Data Collection: Gather data on pre-EVA radiation exposure, genetic factors, suit pressurization data, and environmental conditions.
o Feature Engineering: Include radiation exposure metrics, temperature impacts, genetic predisposition markers, and bubble growth predictions.
o Model Training: Train the model using supervised learning to predict DCS likelihood with combined genetic, environmental, and radiation factors.
3. Real-Time Monitoring System:
o Risk Scoring: Output a risk score for DCS that updates in real-time based on EVA suit telemetry, radiation dose sensors, and blood oxygenation monitors.
o Alert System: Generate alerts when bubble nucleation and growth reach critical thresholds, using the bubble dynamics and flow models integrated with real-time EVA data.

Visualization and Simulation Outputs
Bubble Nucleation and Growth Visualization: Simulate and visualize bubble formation and growth under Mars and Moon gravity, including thermal effects and shockwaves from rapid temperature shifts.

Radiation-Induced Risk Mapping: Use a predictive model to generate risk maps of DCS for different EVA durations and conditions on Mars and the Moon.

Blood Flow and Shockwave Visualizations: Dynamic simulations to show blood flow, bubble behaviour, and shockwave propagation within the body during an EVA.

1. Bubble Formation and Growth in Microfluidic Channels
1.1 Microfluidic Simulation Setup
Microfluidic Design: Microchannels can be engineered to mimic small blood vessels, allowing precise control of gas supersaturation, flow rates, and temperature to simulate conditions on Mars or the Moon.

Key Parameters:
o Channel Width and Geometry: Channel dimensions should resemble small arteries or capillaries (typically in the 10-100 μm range) to study bubble behaviour in small vessels.
o Temperature Control: External heaters or coolers can replicate temperature swings like those encountered on the Moon and Mars.
o Gas Supersaturation: Inducing nitrogen supersaturation in the fluid allows for controlled bubble nucleation, mirroring decompression scenarios in low-pressure environments.

1.2 Bubble Formation Evaluation in Microfluidic Channels
· Experimental Procedure:
o Gas Injection: Controlled nitrogen gas injection into the liquid medium to create a supersaturated state.
o Pressure Modulation: By adjusting external pressure, induce decompression to promote bubble nucleation and growth.
o Microscopy Analysis: Use high-speed cameras and microscopy to visualize and measure bubble size, growth rate, and distribution.

· Data Collection and Analysis:
o Critical Radius of Nucleation (r_crit): Calculate the size threshold for stable bubble formation under simulated Mars and lunar pressures using nucleation theory.
o Bubble Growth Dynamics: Fit observed growth rates to the Rayleigh–Plesset equation to model expansion influenced by temperature and flow dynamics.
o Temperature Influence: Study bubble stability as temperatures are varied within microfluidic channels to represent extreme EVA conditions, recording changes in nucleation rate and bubble dissolution.

2. Sanal Flow Choking and Its Relevance to Bubble Dynamics
2.1 Understanding Sanal Flow Choking
Definition: In compressible fluid flows, Sanal flow choking occurs when the flow rate through a channel reaches a critical limit beyond which it cannot increase, regardless of downstream pressure reductions.

Relevance to Bubble Formation: In microgravity and low-pressure EVAs, Sanal choking can alter the flow dynamics in blood vessels, particularly in gas-saturated fluids, where local pressure drops could lead to rapid bubble growth or even flow obstruction by bubbles.
Critical Pressure Ratio for Choking: The critical pressure ratio for Sanal flow choking can be calculated based on blood properties and flow conditions. For example:

2.2 Microfluidic Experiments for Sanal Flow Choking
Microchannel Design: Introduce narrow constrictions in the microfluidic channel to mimic areas where flow could choke, such as narrow blood vessels under EVA conditions.

Flow Rate Control: Use precise pumps to control fluid velocity

and observe conditions that lead to choking.

Pressure Gradient Measurement: Install pressure sensors upstream and downstream to identify critical pressure points where flow reaches maximum velocity (choking point).

$$\frac{P_2}{P_1} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

where:

- P_2 = Downstream pressure.
- P_1 = Upstream pressure.
- γ = Specific heat ratio, influenced by blood's thermal properties.

Observations:
o Bubble Response to Choking: Measure the behaviour of bubbles near the choking region, particularly their expansion or collapse.
o Pressure-Induced Nucleation: Observe if choking causes localized low pressures that trigger additional bubble nucleation and growth.

Data Analysis:
o Flow Velocity Limits: Determine flow velocities and conditions that lead to choking, correlating these with bubble behaviour to assess choking risk under EVA-like conditions.
o Predictive modelling: Develop a predictive model for Sanal choking thresholds in blood based on experimental data and integrate it into the AI model to better predict bubble formation risks.

3. Shockwave Generation and Propagation
Shockwaves in blood due to rapid decompression or sudden changes in pressure near bubbles are significant factors in DCS. In microfluidic experiments, we can simulate these shockwave phenomena in a controlled environment to study their effects.

3.1 Shockwave Dynamics in Bubble-Containing Fluids
Shockwave Sources:
o Rapid Bubble Expansion/Collapse: Microfluidic experiments can trigger sudden decompression to induce rapid bubble expansion, which generates shockwaves.
o Controlled Acoustic Shockwaves: Apply external acoustic shockwaves to microchannels to study how these waves interact with bubbles and influence bubble stability.

Key Parameters:
o Shockwave Intensity and Frequency: Simulate EVA-relevant shockwave frequencies and pressures to assess bubble responses.
o Medium Properties: Use blood-mimicking fluids to understand how shockwave propagation varies in a biological medium.

3.2 Microfluidic Experiments for Shockwave-Bubble Interactions
High-Speed Imaging: Capture bubble dynamics and shockwave propagation through high-speed cameras in microfluidic channels.

Pressure and Acoustic Sensors: Install sensors along the channel to detect shockwave strength and observe pressure fluctuations.

Variable Pressure Control: Use rapid decompression mechanisms to mimic scenarios astronauts could encounter during EVA decompression.

3.3 Analysis of Shockwave Impacts on Bubble Behaviour
Rayleigh Collapse Model: Apply the Rayleigh collapse equation to model bubble collapse under shockwave impact:

$$R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{1}{\rho}\left(P_{\text{shock}} - P_\infty - 4\frac{\mu}{R}\frac{dR}{dt} - \frac{2\gamma}{R}\right)$$

where P_{shock} is the pressure from the shockwave.

where P shock is the pressure from the shockwave.
Bubble Fragmentation and Jetting: Analyse whether bubbles fragment or emit jets upon collapse under shockwave impact, which could exacerbate cellular damage.

Shockwave Attenuation: Measure the attenuation of shockwaves as they travel through the fluid, which is essential for predicting how shockwaves would dissipate in human blood under Mars or Moon EVA conditions.

4. Integrating Experimental Insights into the AI Model for EVA Conditions
Each aspect of these microfluidic experiments can help refine the AI model for predicting decompression sickness (DCS) during Mars and Moon EVAs:

1. Bubble Nucleation and Growth Model:
o Incorporate experimental data on bubble formation thresholds, critical radii, and growth rates under simulated Mars and lunar conditions.
o Adjust the AI model to better predict bubble stability and growth in the bloodstream by integrating temperature and pressure response curves derived from microfluidic experiments.

2. Sanal Choking and Flow Dynamics:
o Use microfluidic choking data to determine the conditions under which choking occurs in the circulatory system under EVA pressure conditions.
o Integrate a choking risk factor into the AI model to predict regions of potential flow stagnation or obstruction due to bubbles.

3. Shockwave Propagation and Cellular Risk:
o Feed experimental data on shockwave-bubble interactions into the model to predict areas of increased cellular damage risk due to bubble collapse.
o Add a shockwave impact variable in the AI model that adjusts DCS risk based on EVA decompression rates and potential shockwave exposure.

Expected Outputs and Visualizations
1. Bubble Formation and Stability Maps: Real-time maps predicting bubble nucleation sites, sizes, and growth rates across the bloodstream under Mars and lunar conditions.
2. Choking and Obstruction Alerts: Predictive alerts for Sanal flow choking risks during EVAs, with flow visualizations indicating regions of potential blood flow obstruction.
3. Shockwave Damage Visualizations: Simulated shockwave propagation through the bloodstream and expected bubble fragmentation, providing insights into cellular damage likelihood in response to decompression shockwaves.

1. Real-Time Telemetry Data Integration
Real-time telemetry can enhance the predictive accuracy of DCS models by incorporating data on astronauts' vital signs, environmental variables, and EVA suit parameters.

1.1 Telemetry Variables for EVA DCS Prediction
Telemetry data should include:
Vital Signs: Heart rate, blood oxygenation (SpO_2), and respiration rate, which influence blood pressure and flow dynamics.

Suit Pressure and Temperature: Variations in EVA suit pressurization and temperature control affect internal blood pressure, which impacts bubble stability.

Radiation Dosimetry: Radiation exposure metrics should be

fed into the AI model in real-time to adjust risk scores based on cumulative exposure.
Decompression Rates: Monitor decompression schedules, particularly in low-pressure environments like those on the Moon and Mars.

1.2 Data Collection and Preprocessing
Data Storage: Use a cloud-based telemetry system to store and analyse incoming data, enabling AI to assess DCS risk dynamically.

Feature Engineering: Transform telemetry data into features relevant to DCS prediction, such as flow rate changes, pressure gradients, and estimated bubble sizes).

2. Microfluidic Experiments for Informed AI modelling
Microfluidic experiments provide real-world data that support and validate AI model predictions for DCS risk.

2.1 Bubble Formation in Simulated Space Conditions
Experimental Setup: Use microfluidic channels designed to mimic the diameters of small blood vessels. The setup should allow for precise control over temperature, pressure, and gas saturation to simulate Mars and Moon conditions.
Pressure Modulation: Vary pressure across channels to study decompression effects and capture critical nucleation thresholds using high-speed imaging. Such experiments provide insights into bubble growth rates and stability.

2.2 Sanal Flow Choking Dynamics
Relevance of Flow Choking: Sanal flow choking impacts fluid flow in constricted vessels, particularly under reduced gravity, where blood flow might stagnate or choke in narrow channels. This phenomenon is critical in DCS modelling, as stagnated flow can promote bubble accumulation.
Microfluidic Testing: Create constrictions within the channels to observe conditions under which Sanal choking occurs. The choking threshold for microgravity conditions can be experimentally determined and fed into the AI model as a "choking risk" feature.

2.3 Shockwave Generation and Propagation
Shockwave Simulation: Generate shockwaves in microchannels by rapid decompression or external acoustic shock to study their interactions with microbubbles. Capturing how shockwaves affect bubble integrity provides insight into potential cellular damage risks.
High-Speed Imaging and Sensor Data: Capture shockwave propagation and bubble fragmentation in high-speed imagery. This data can improve the AI model's capability to predict regions where shockwave-induced cell damage may occur in response to EVA decompression.

3. Integrating Experimental and Telemetry Data into AI Models
3.1 Real-Time Monitoring and Alert System
Risk Scoring: Feed experimental parameters—such as bubble stability and flow choking data—along with real-time telemetry to generate continuous DCS risk scores.

Predictive Analytics: Use predictive analytics based on past EVA data, microfluidic experiment results, and telemetry to alert astronauts to risky DCS thresholds before symptoms appear.

3.2 Machine Learning Pipeline
Feature Extraction: Use machine learning to analyse bubble dynamics, flow rates, pressure, and telemetry to predict DCS likelihood, combining experimental findings with in-mission telemetry.

Validation and Model Tuning: Validate the AI model against historical astronaut health data and microfluidic experiments. Fine-tune based on real-time telemetry to ensure model predictions remain accurate under varying conditions.

DISCUSSION

Decompression sickness (DCS), or "the bends," occurs when nitrogen dissolved in bodily fluids forms gas bubbles due to rapid decompression, such as during extravehicular activities (EVAs) in space. This condition can lead to severe joint pain, dizziness, paralysis, and even fatal outcomes if untreated. Astronauts are particularly susceptible due to the unique space environment, including microgravity, low external pressures, and exposure to radiation.
1. Cardiovascular System: Rapid decompression causes nitrogen bubbles to form in blood vessels, obstructing blood flow and potentially leading to ischemia or embolism.
2. Respiratory System: Gas bubbles in the lungs can trigger respiratory distress or cause emboli that impair oxygen delivery.
3. Musculoskeletal System: Bubbles can form in joint spaces, causing intense pain (often in shoulders or knees) and reduced mobility, commonly reported as "joint bends."
4. Central Nervous System: In severe cases, bubbles can lodge in brain or spinal tissues, leading to neurological symptoms such as confusion, vision disturbances, and paralysis.

Preventative Systems And Protocols:

Pre-breathing Protocols: Astronauts pre-breathe pure oxygen to remove nitrogen from tissues before EVAs.
Pressurized Suits: Spacesuits maintain pressure to minimize decompression rates.
Real-Time Monitoring: Sensors in EVA suits track vital signs, enabling real-time adjustments and alerts for decompression-related risks.

This integrated approach helps mitigate DCS risks but requires continuous research and advanced modelling to improve safety during space missions.

CONCLUSION

This comprehensive approach to studying microbubble formation in decompression sickness of astronauts and AI based risk prediction with real time EVA conditions through telemetry, microfluidics helps in early detection and mitigation of risks involved. Use of specific pre breathing gas mixture ratios based on planet atmosphere and use of focussed ultrasound for microbubble rupture needs further studies.

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