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THE APPLICATION OF INTEGRATED KNOWLEDGE-BASED SYSTEMS FOR THE BIOMEDICAL RISK ASSESSMENT INTELLIGENT NETWORK (BRAIN)

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ABSTRACT

One of NASA's goals for long duration space flight is to maintain acceptable levels of crew health, safety, and performance. One way of meeting this goal is through the Biomedical Risk Assessment Intelligent Network (BRAIN), an integrated network of both human and computer elements. BRAIN will function as an advisor to flight surgeons by assessing the risk of in-flight biomedical problems and recommending appropriate countermeasures. This paper describes the joint effort among various NASA elements to develop BRAIN and an Infectious Disease Risk Assessment (IDRA) prototype. The implementation of this effort addresses the technological aspects of: (1) knowledge acquisition, (2) integration of IDRA components, (3) use of expert systems to automate the biomedical prediction process, (4) development of a user-friendly interface, and (5) integration of the IDRA prototype and Exercise Countermeasures Intelligent System (ExerCISys). Because the C Language, CLIPS (the C Language Integrated Production System), and the X-Window System were portable and easily integrated, they were chosen as the tools for the initial IDRA prototype. The feasibility was tested by developing an IDRA prototype that predicts the individual risk of influenza. The application of knowledge-based systems to risk assessment is of great market value to the medical technology industry.

INTRODUCTION

One of NASA'S primary goals for space flight is to maintain acceptable levels of health, safety, and performance of the crew. To achieve this goal, medical teams have monitored the health of the crew pre-flight, in flight, and post flight throughout the history of manned space programs. During the Skylab missions, in-flight biomedical data were used as a basis for making decisions about the flight duration of successive Skylab missions (21). The medical team had to plan very carefully for a quick turn-around time of sample processing and data analysis between missions. The Skylab Medical Management Group met daily to review the status of the crew. Without computer assistance this activity was very man-hour intensive and undoubtedly increased the cost of the operations.

For extended tours of duty on Space Station Freedom and Lunar/Mars stations, a greater effort will be required to assure nominal crew operations. To achieve this, NASA will monitor crew physiological, psychological, and task performance and administer appropriate countermeasures (17,22,31,39). It may be crucial to assess quickly the individual risk of biomedical problems based on changes in certain physiological, psychological, or environmental indicators to initiate countermeasures (10,19). It is important to predict the impact of the selected countermeasures on crew health, safety, and performance. If more than one change in crew status is observed, it is critical to evaluate each countermeasure relative to the others.

Automation technology is required to support this decisionmaking process. It reduces the volume of data, facilitates data interpretation, and resolves incompatible data. For example, expert or knowledge-based systems can automate the medical diagnostic process (20,28,42). The knowledge that is represented in medical textbooks and/or the expertise of a physician is incorporated into computer software (13). These systems handle a large quantity of related physiological or anatomical data; however, each expert system is developed for only one specific discipline (5,6,7).

Expert systems are commonly implemented as rule-based production systems based on a series of "if...then" reasoning rules (13). The Software Technology Branch at NASA/Johnson Space Center has developed a rule-based production system called CLIPS, the C Language Integrated Production System (9,12,38). CLIPS is being used to automate the prediction process of the IDRA prototype (see below) and BRAIN.

NASA has supported the development of four life sciences expert systems for use on long duration space flight:

- The IDRA prototype assesses the risk of infectious diseases and recommends countermeasures to reduce the risks. The implementation approach and the results of this development are presented in this paper.

- The ExerCISys prescribes an exercise protocol to maintain muscle strength and cardiovascular aerobic capacity in flight.

- The Medical Equipment Computer (MEC) provides decision-support for disease diagnosis and drug therapy in flight.

- The Performance Prediction Model (PPM) assesses the effect of environmental and mission factors on the team performance and predicts its level accordingly. This project is in the early stages of development.

The limitations of these expert systems are that they are independent from each other. They are designed for a single user, and the data are not automatically shared between systems or users. A solution to the problems associated with multiple expert systems is the Biomedical Risk Assessment Intelligent Network (BRAIN). The application of knowledge-based systems or artificial intelligence is a vital component of BRAIN. BRAIN is an integrated network for biomedical risk assessment and management. It provides a composite of multiple experts similar to that generated by the Medical Management Group during the Skylab missions. We hypothesize that BRAIN will reduce the time required for a flight surgeon to arrive at real-time decisions about individual biomedical risk analysis and management. This paper describes an implementation approach to develop a BRAIN prototype and the development of an IDRA prototype to test the feasibility of the approach.

Others outside NASA will benefit from the development of BRAIN. Institutions such as hospitals, medical clinics, boarding schools, military services, nursing homes for the mentally and physically handicapped, and home medical care services are potential users.

IMPLEMENTATION APPROACH

Documentation of Requirements

The BRAIN concept is illustrated as a triangle (Figure 1) with users on the left side and expert systems on the right side. The network still permits each user and system to work independently and interact independently with the flight surgeon. Through BRAIN, each system may access pertinent data from other systems. BRAIN cooperates with the independent expert systems by use of a knowledge base that relates all of them.

The functions of BRAIN are to:

- access IDRA, ExerCISys, MEC, PPM, and other undefined separate systems for pertinent information.

- assess a composite biomedical risk and recommend countermeasures.

- function as a clearing house of information to be shared between systems.

- resolve incompatible information given by other expert systems and derive a composite recommendation for a flight surgeon.

The preliminary software requirements of BRAIN will be documented according to the IEEE Standards Board and the American National Standards Institute (2).

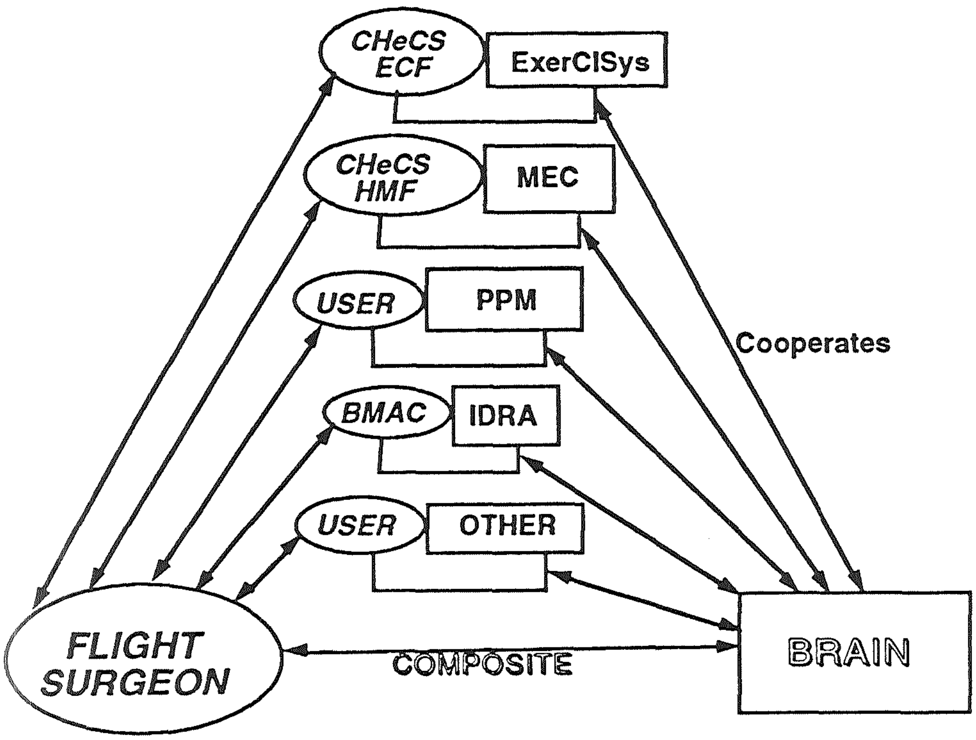

Figure 1. **The BRAIN Concept.** The users on the left interact verbally with the flight surgeon and mechanically with each independent expert system. BRAIN cooperates with each expert system using a knowledge base that relates all of them. A composite recommendation is then presented to flight surgeon for real-time decisionmaking. (CHeCs-Crew Health Care System, ECF-Exercise Countermeasures Facility, HMF-Health Maintenance Facility, BMAC-Biomedical and Countermeasures)

System Design

Knowledge Definition

A major activity of this project is to develop the knowledge-based system design. This includes the identification of data sources, knowledge definition, knowledge design, and the architecture of the hardware/software environment for BRAIN. The knowledge definition task defines the knowledge requirements of the network and identifies and selects the knowledge sources. The knowledge is acquired, analyzed, and extracted. The knowledge design comprises the knowledge representation, i.e., rules, internal fact structure, detailed control structure, and preliminary user interface (13).

BRAIN receives input from and gives it to PPM, IDRA, MEC, and ExerCISys, or the user, as illustrated in Figure 1. Other data that are required by BRAIN reside in a separate data base, are retrieved as necessary, and are stored in a local or working data base. Unknown data or inaccessible data may be simulated for the version 1.0 development.

The data structure and network configuration of BRAIN must be compatible with IDRA, ExerCISys, MEC, and PPM. These expert systems share related data through BRAIN by accessing the working data base. We will test the feasibility of IDRA, ExerCISys, MEC, and PPM to regularly post data that are required by other systems. A standard protocol will be established for each system to access BRAIN and vice versa.

The knowledge base for BRAIN utilizes and interprets the data, predicts the risk of biomedical problems and recommends the appropriate countermeasures. The information in the data base is extracted from the sources such as:

- *Spaceflight Historical Information*
- *Expert Medical and Science Personnel*
- *Texts, Journal Article and Reviews*
- *Epidemiological Studies of Normal Populations*

The resources available in the medical sciences arena and NASA life sciences groups are explored for the knowledge definition of BRAIN. The relationships among IDRA, ExerCISys, MEC, and PPM are defined by means of workshops, personal consultation and collaboration of existing study results. Experts e.g. flight surgeons or scientists, will be identified and interviewed to model their expertise and to evaluate the demonstration of BRAIN during the developmental stages.

Knowledge Acquisition

Once the knowledge base has been defined for BRAIN, methods will be developed to acquire the specific knowledge. Because a great deal of knowledge has to be acquired for BRAIN, an automated method may be required for that purpose. Several knowledge acquisition tools will be evaluated for consistency and reproducibility in extracting information from human experts and written sources.

The investigative team has access to and experience with several automated knowledge acquisition tools (e.g., Design Alternatives Rationale Tool [DART], Nextra, Task Analysis/Rule Generating Tool [TARGET], Knowledge Acquisition and Representation Tool Kit [KART], and Knowledge Network Organizational Tool [KNOT]).

Nextra operates as a knowledge acquisition front-end tool to an expert system development package called Nexpert Object. Both tools are marketed by Neuron Data from Palo Alto, CA. Nextra allows users to graphically represent entity relationships between the various elements of a subject or domain. DART is another tool that analyzes design alternatives and their associated rationale knowledge. Both Nextra and DART tools can address problems concerned with taxonomies and classification. Both also use repertory-grid knowledge representations. The relationship among the outputs of MEC, ExerCISys, IDRA, and PPM will be examined with these tools in order to derive appropriate rules for biomedical risk assessment. New tools may have to be developed to acquire the appropriate knowledge for BRAIN.

Although various types of expert knowledge exist within the NASA environment, procedural knowledge is prevalent in many areas including the biomedical environment. A procedural analysis tool, TARGET, models a set of actions or procedures associated with a task using a graphical user interface. This tool will be tested to analyze the procedure used by a flight surgeon to solve problems associated with the recommendations given by MEC, ExerCISys, IDRA, and PPM. The specific details will be defined during the knowledge definition phase of the project.

Knowledge Design

A conceptual design of BRAIN is illustrated in Figure 2. Further definition of the knowledge representation and design is delayed until knowledge acquisition is completed. At that time, more will be known about the structure of the knowledge and how it can best be represented.

It is anticipated that the knowledge may be subjected to a software tool called RuleMaster that uses the Iterative Dicotomizer (ID) 3 algorithm. The ID3 algorithm analyses empirical data and derives rules for the knowledge base of BRAIN. Advanced techniques, e.g. CLIPS, will be tested to automate the biomedical prediction process. Other existing and newly-developed tools will be evaluated for their best knowledge representation and design capability.

BRAIN will be designed with a learning capability. It will incorporate, by a feed-back mechanism, the experience of a human expert. The decisions and interpretations of data obtained from actual test cases are acquired automatically in the knowledge base and new rules are induced.

This function is entirely under the control of the appropriate user. But once initiated, it is automatically included in the knowledge base.Tools such as the Automated Reasoning Tool (ART) and Automated Structured Rule Acquisition (ASTRA) are being used to capture the expertise of exercise physiologists for ExerCISys. ART and ASTRA are being evaluated for application to BRAIN.

Knowledge Verification/Validation

Verification and validation of BRAIN is a vital step throughout the life cycle of its development (18). Verification of BRAIN determines that the software is developed according to specifications. The knowledge base will be verified by checking specific details to the level of each rule.

Validation determines that BRAIN performs the functions as specified by the requirements and is usable for field testing (11). Validation of BRAIN will encompass aspects of the validation process such as determining the validation criteria and developing a library of test cases and detailed space flight scenarios that are described in (11) and (27).

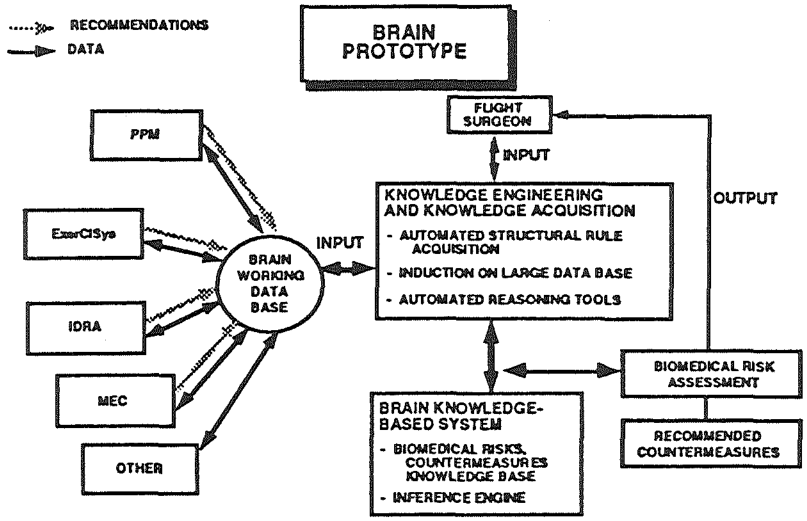

Figure 2. Conceptual Design of BRAIN. The working data base is integrated with IDRA, ExerCISys, MEC, PPM, and additional data bases that contain the facts required by the network, e.g. countermeasures. The expertise of flight surgeons is also captured during the knowledge acquisition process and rules are automatically induced to reflect this expertise. All the rules are stored in the knowledge base and the inference engine executes the appropriate rules for a given working data base.

After the Preliminary Design Review of the project, the detailed design description will be documented. It will specify the logic and content of the knowledge base, the implementation of the system, hardware requirements, the detailed user interface, and the detailed demonstration plan.

The hardware/software environment of BRAIN will be compatible with MEC, PPM, IDRA, ExerCISys, and Space Station Freedom standards to communicate related information. The development environment that is used to create the software may not run on the identical platform as the demonstration version.

User Interface

It is essential for the flight components of BRAIN to have user friendly interfaces. Ease of use may determine whether or not a system is fully utilized. Early prototypes will be developed with prototyping tools to explore the user interface. The user interfaces to BRAIN will be designed in accordance with human factors principles (43) and the Space Station Volume of the Man Systems Integration Standards (NASA STD 3000) document (26). In addition, the user interface code will be portable and compatible with the Space Station Freedom Data Management System. Some of the factors that will be addressed are information grouping, user system dialogs, and information highlighting techniques. Prior to completion of the final BRAIN design, all interfaces will be empirically evaluated using subjects similar to the typical user. Based upon findings of this study, the design of the interfaces will be refined. The final product is BRAIN, version 1.0, that will have been tested and proven to function as an integrated network of the MEC, IDRA, ExerCISys, and PPM prototypes, with a validated, well-designed user interface.

FEASIBILITY TESTING

The IDRA Prototype

The feasibility of using integrated knowledge-based systems for biomedical risk assessment was tested in the IDRA prototype. Because the prevention of infections during manned space flights is important (3,30,35), the IDRA prototype was developed initially to assess the probability of influenza infection.

The epidemiology of and procedures for preventing, diagnosing, and treating influenza are well defined (1,4,40). Epidemiological studies have evaluated the risk factors and their predictive value for influenza in the general population (8,14,25,37,41) and the efficacy of chemotherapeutic prophylaxis (15). Earlier studies investigated the outbreak of influenza in isolated populations, e.g., on an aircraft (29), a ship at sea, (34) and college campuses (24,36). From these sources, we concluded that sufficient information was available to construct a knowledge base about influenza.

The Integration of IDRA and ExerCISys

Studies indicate that exercise has a profound effect on the immune system (23,32,33), sometimes inducing changes similar to those arising from the stress of space flight (16). Therefore, exercise regimen and related physiological data are factors that must be taken into consideration for the risk assessment of infectious diseases and for prescribing an exercise program. This was suggested on the Soviet MIR Space Station when Cosmonaut Gennady Strekalov "caught a cold" following exercise (reported by the Associated Press, October 18, 1990).

The IDRA prototype is compatible with the ExerCISys prototype, and we will integrate IDRA with the ExerCISys as a model for BRAIN. When BRAIN is actually implemented as described in the approach, BRAIN, IDRA, and ExerCISys will be separate systems. However, to test the feasibility of integrating two independent systems initially, the integrated knowledge base will reside in the IDRA prototype. This also provides an opportunity to evaluate the type of information that will be shared and what will remain private between the systems. When the requirements for BRAIN are better defined, the integrated knowledge base will be moved to a separate hardware and software environment, and all systems will be connected to BRAIN through a network communications link.

IDRA Preliminary Results

The knowledge for the IDRA knowledge base was extracted and analyzed from textbooks and journal articles cited above. We identified the critical indicators that predict the probability of influenza. The risk of influenza for an individual is described by general population statistics. It depends on an individual's location, age group, and level of immunity. This information is encoded in a set of 40 rules using CLIPS. Two examples of the rules are in Table I. A subset of these rules incorporates the effect of exercise on the risk of infections. Depending on the individuals condition at any given point in time, a risk of influenza can be assessed based on epidemiological data and the individual's medical record. Once the communication link is completed between the IDRA prototype and the ExerCISys prototype, IDRA will query ExerCISys for the level of fitness of each subject based on aerobic capacity. This information will execute additional rules by IDRA that generate a risk assessment of influenza. The prototype requires further development, validation, and testing.

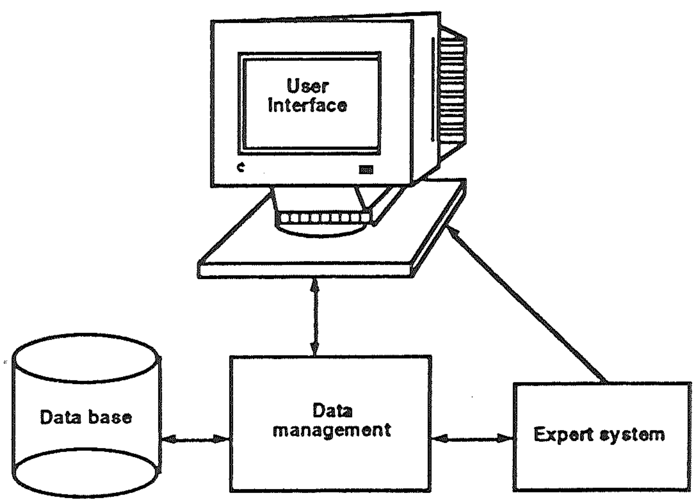

Figure 3. Major Components of the IDRA Prototype

Figure 3 illustrates the major components of the IDRA prototype. A C-based data manager interacts with all the components of the system. It processes information from the data base and from the user interface. The expert system using CLIPS assesses the probability of influenza. It retrieves the information from the data manager and outputs it to the user interface. For the preliminary user interface, we used the X-Window System. The probability of infection and illness is displayed in the form of text and a graph. All tools are portable and compatible with Space Station Freedom requirements. The preliminary results suggest that an integrated IDRA prototype is feasible and can serve as a model to develop BRAIN.

Table I. Examples of IDRA Rules. The normal state is defined by a., and the effect of moderate exercise is defined by b.

```
a. (defrule normal-state"
   (phase disease-prediction)
   (personal-data (name ?name) (identification ?id)
                  (ages ?x&: (or (<?x 18) (> ?x 64)))
                  (environment normal) (location ~Houston)
                  (nasal-sIgA ?n&: (< ?n 2.75)) (flu-vaccination ~yes))
                  (amantadine no) (flu-exposure no) (exercise light))

=>
(update-risk-factor ?id 0.527 0.428); 0.527 is mathematically calculated
(printout t "Subject        : " ?name crlf)
(printout t "Identification : " ?id crlf)
(printout t "age            : " ?x crlf)
(printout t "has a 42.8% chance to get influenza illness due to the age" crlf)
(printout t " and lacking of NASAL sIgA" crlf crlf))
```

```
b. (defrule moderate-exercise-state
   (phase disease-prediction)
   (personal-data (name ?name) (identification ?id)
                  (ages ?age) (location ?)
                  (environment ~crowded)
                  (nasal-sIgA ?n&: (< ?n 2.75)) (flu-vaccination ~yes)
                  (amantadine no) (flu-exposure no) (exercise moderate))

=>
(update-risk-factor ?id 0.38 0.28)
(printout t "Subject :" ?name crlf)
(printout t "Identification  : " ?id crlf)
(printout t "age             : " ?age crlf)
(printout t "has only a 28% chance to get influenza illness due to" crlf)
(printout t "moderate exercise" crlf)
(printout t "and lacking of NASAL sIgA" crlf crlf crlf))
```

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