# A Semio-Fuzzy Approach to Information Fusion in the Diagnosis of Obstructive Sleep Apnea


M. Kwiatkowska
*Department of Computing Science*
*University College of the Cariboo*
*Kamloops, BC V2C 5N3, Canada*
mkwiatkowska@cariboo.bc.ca

M. S. Atkins
*Department of Computing Science*
*Simon Fraser University*
*Vancouver, BC V5A 1S6, Canada*
stella@cs.sfu.ca



***Abstract* – This paper combines the fuzzy logic approach with a semiotic framework to model the information fusion in diagnosis of obstructive sleep apnea. It describes the conceptualization, operationalization, and utilization of measures used for sleepiness, a crucial symptom of sleep disorders. The semiotic framework defines the relations between the concept of sleepiness, its representations, and interpretation. The fuzzy inference system utilizes the sleepiness membership functions constructed by sleep experts and the semio-fuzzy rules. The example of three symptoms: sleepiness, snoring, and high blood pressure, illustrates the importance of the explicit semiotic knowledge representation.**


## I. Introduction

Obstructive sleep apnea (OSA) is a common and serious respiratory disorder afflicting approximately 2-4% of the general population [1]. OSA is caused by the collapsing of the soft tissues in the throat as the result of the natural relaxation of the muscles during sleep. The sleeping person literally stops breathing ("apnea" means "without breath"). Since sleep apnea occurs only during sleep, it might be unnoticed for years. The diagnostic process uses heterogeneous data of diverse granularity, uncertainty, and precision, and originating from several sources: patients, medical professionals, and medical diagnostic equipment [2]. The data is grouped into two categories: 1) *subjective*, which is based on self- and other-reporting using instruments such as sleep questionnaires, standardized scales, a sleep diary, and bed-partner reporting; 2) *objective*, which involves medical examination, overnight polysomnography (PSG) performed in a specialized sleep clinic, and home sleep studies (home PSG, limited studies). The golden standard in diagnosis of OSA is an overnight in-laboratory PSG. However, this is an expensive and not readily available test. British Columbia has only five sleep clinics located in its major cities. Many patients are waiting for 6-12 months for a single night study (the treatment of OSA may require more than one study) [3]. Therefore, with the proliferation of portable diagnostic devices and the developments in telemedicine, there is a growing interest in computer-aided systems for OSA screening [4]. Such a system will provide the acquisition of subjective and objective data as well as an initial evaluation of the symptoms for OSA risk factors.

The existing fuzzy logic approaches [5,6] to computer aided diagnosis and modeling methods focus on either the *objective* data or the *subjective* data. However, in medical practice, the sleep study interpretations, diagnosis and treatment are based on information integrated from both types of data.

### *A. Sleepiness (Somnolence) in the Diagnosis of OSA*

Daytime Sleepiness is one of the most important symptoms of OSA and is used for screening, evaluation, and classification of the severity of OSA [7]. The typical complaints of OSA patients (or their family members) are excessive sleepiness, fatigue, and snoring. However, sleepiness is not a universal symptom; about 10% patients with OSA do not display excessive sleepiness.

At first, patients are assessed by their family doctors and referred to specialized sleep disorder clinics. The initial assessment process involves looking at several risk factors such as sleepiness, snoring, high blood pressure, high BMI (body mass index), witnessed breathing pauses, morning headaches, smoking, age, and gender. The final diagnosis of OSA is based on the results from polysomnography (PSG) combined with the results of a sleep questionnaire and the patient's medical history. One of the important elements of the diagnosis is the classification of the severity of OSA, which, in turn, is used for determining appropriate treatment (for example, CPAP mask is recommended for moderate OSA).

The International Classification of Sleep Disorders (ICSD) [2] defines the severity of OSA in terms of the frequency of respiratory events (pauses in breathing longer than 10 seconds), the degree of oxygen desaturation, and the severity of daytime somnolence (sleepiness). The ICSD classification is described in Table 1.

TABLE 1

SEVERITY OF OSA (ADAPTED FROM [2])

| OSA Severity | Respiratory Events/ Hour | Oxygen desaturation | Daytime somnolence |
|---|---|---|---|
| Mild | 5-14 | Mild | Mild |
| Moderate | 15-29 | Moderate | Moderate |
| Severe | =30 or >30 | Severe | Severe |

Although the term *sleepiness* is used extensively in the OSA pre-assessment, diagnosis, and treatment, it is poorly defined and often confused with fatigue [8]. In this paper we combine two frameworks: 1) semiotic approach for conceptualization, operationalization, and utilization of sleepiness measurements; and 2) fuzzy membership functions and fuzzy inference system (FIS) for knowledge representation and symptoms analysis. The semiotic approach is introduced in section II. The fuzzy membership functions for sleepiness and fuzzy inference system are described in section III. An integration of semiotic and fuzzy logic is illustrated by a semio-fuzzy rule in section IV. Finally, conclusions and plans for further work are presented in section V.

## II. The Semiotic Framework

Originally, the term 'semiotics' (from a Greek word for sign 'semainon') was introduced in the second century by the famous physician and philosopher Galen (129-199), who classified semiotics (the contemporary *symptomatology*) as a branch of medicine [9]. The use of term *semiotics* to describe the study of signs was developed by the Swiss linguist Ferdinand de Saussure (1857-1913) and the American logician and philosopher Charles Sanders Peirce (1839-1914). Originally, Saussure used the term 'semiology' and Peirce 'semeiotic', but both terms correspond to today's usage of the word 'semiotics.' Peirce defined 'sign' as any entity carrying some information and used in a communication process. Since signs and communication are present in all sciences, the semiotic approach has been used in almost all disciplines, from mathematics through literary studies to ethnography, including information systems and computational semiotics [10,11].

Peirce, and later Charles Morris, divided semiotics into three categories [12]: *syntax* (the study of relations between signs), *semantics* (the study of relations between signs and the referred objects), and *pragmatics* (the study of relations between the signs and the agents who use the signs to refer to objects in the world). This triadic distinction is represented by a Peirce's semiotic triangle: *object*, *representation*, and *interpretant*. The notion of 'interpretant', one of the most complex in Peirce's theory, is represented in this paper by a set of pragmatic modifiers: 1) *agents* (for example: patients, health professionals, medical sensors, computer systems), 2) *perspectives* (for example: health care costs, accessibility, ethics), 3) *contexts* (for example: time of the day), 4) *biases* (for example: specific subgroups of agents), and 5) *views* (for example: variations in the diagnostic criteria used by individual experts or clinics). Pragmatic modifiers have some similarities, but are not identical to the semiotic descriptors introduced by Kohout [13]. Peirce's semiotic triangle is illustrated in Fig. 1.

In Peircean model [12], the relation between an object and its representation has three possible modes: *symbolic*, *iconic*, and *indexical*. In a symbolic relation, the sign does not resemble the object and the relation is conventional or arbitrary, for example an expression in natural language. In an iconic relation, the sign is perceived as resembling the object, for example a recorded sound or picture. In an indexical relation, the sign is directly connected with the object, for example, patient's temperature or blood pressure. However, these modes may co-exist in the same sign and the dominating mode is determined by the usage (for example, context).

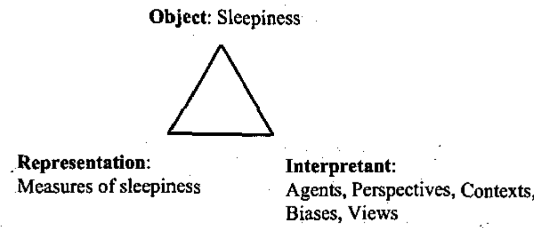


Fig. 1 Peirce's semiotic triangle

### A. Measuring Sleepiness

The symptom of *sleepiness*, although extensively used in screening and diagnosis, is not easy to describe and, moreover, to quantify. Sleepiness can be measured only indirectly – there is not yet a single laboratory test to identify 'sleepy' individuals. The *excessive daytime sleepiness* (EDS) is considered to be the most important indicator of sleep disorders [14], but how can one measure sleepiness and what does it mean to be excessively sleepy?

The measuring process involves three aspects: *conceptualization* (what to measure), *operationalization* (how to measure), and *utilization* (how the measure is used) . These three aspects are mapped to the semiotic triangle. The symptom S is defined by a triplet S = <O,M,U>, where O represents a set of objects, M a set of measures, and U a set of utilization parameters.

The following subsections describe the ontological aspects of the concept, semantic aspects of different measures, and pragmatic aspect of the measure in the context of its practicality (accessibility) and costs.

### B. Conceptualization of sleepiness

In context of sleep medicine, the word 'sleepiness' has two meanings: 1) in common usage, sleepiness is associated with fatigue or tiredness, and 2) in specialized medical usage, sleepiness is often called 'somnolence' and defined as the inability to maintain wakefulness [15] or a strong sleep propensity [2].

Sleep literature describes the concept of *sleepiness* using three perspectives: *biological*, *behavioural*, and *psychological*. These perspectives correspond to three categories of sleepiness:

1) *Physiologic sleepiness* – biological drive to sleep, (physiological parameters: breathing, cardio-vascular, oculomotor, skin conductance and temperature).
2) *Manifested sleepiness* - decrease in performance motor activity, memory, cognition; observable behaviours: head

nodding, facial expressions, eye movement, blinking, yawning.

3) *Introspective sleepiness* - subjective feeling of being not alert and falling asleep.

Furthermore, sleepiness has transient and persistent qualities. The temporal dimension of sleepiness results in two additional categories:

1) *State sleepiness* – occasional sleepiness lasting for one or two days, due to occasional sleep deprivation or circadian rhythm disruptions (shift work or jet lag).
2) *Trait sleepiness* – permanent sleepiness due to chronic sleep deprivation, sleep disorders, or other medical conditions.

In addition, sleepiness is diagnostically graded using terms such as 'normal', 'excessive', and 'severe'.

### C. Operationalization of Sleepiness

Sleep research and clinical diagnostics have developed several measures for different aspects of sleepiness. This section describes the measures used clinically (concentrating on instruments recommended by the British Columbia Medical Association) [16,17]. In general, the sleepiness measures are classified into two groups:

1) *objective* measures: Multiple Sleep Latency Test (MSLT) and Maintenance of Wakefulness Test (MWT).
2) *subjective* measures: Epworth Sleepiness Scale (ESS), Stanford Sleepiness Scale, and sleep logs.

The Multiple Sleep Latency Test (MSLT) is performed in a sleep disorders clinic after an overnight polysomnography. It lasts about 10 hours and the patient is asked to have 4-5 naps every 2 hours in a quiet place. The sleep latency (the time a person takes to fall asleep) is measured using the PSG equipment.

The Maintenance Wakefulness Test (MWT) is an objective test of alertness, which is very similar to MSLT, with the difference being that the patients are asked to stay awake.

The Epworth Sleepiness Scale (ESS) [18] is the most often used self-administered questionnaire to measure trait sleepiness in eight everyday situations: 1) sitting and reading, 2) watching TV, 3) sitting inactive in public place (e.g. a theatre or a meeting, 4) as a passenger in a car for an hour without a break, 5) lying down to rest in the afternoon when circumstances permit, 6) sitting and talking to someone, 7) sitting quietly after lunch without alcohol, and 8)in a car, while stopped for a few minutes in traffic. Each item has a score between 0-3. The answers are 'never',''slight chance', 'moderate chance', 'high chance.' The maximum score is 24. Typically the score of 11 and above is recognized as *excessive daytime sleepiness* (EDS). ESS is recommended by the British Columbia Medical Association and it is used the sleep clinics in BC.

The Stanford Sleepiness Scale (SSS) is a self-reporting instrument measuring state sleepiness. Patients are grading their state of alertness on a scale from 1-7; 1 corresponding to alert and 7 to falling asleep. The score above 3 indicates sleepiness.

Sleep logs are used to record a daily pattern of sleep and wake for at least seven days. This subjective self-reporting method might be validated by the use of additional actigraphy (objective recording of the patient's hand or leg movements).

Table 2 summarizes the sleepiness measures used in clinical settings.

TABLE 2
SLEEPINESS MEASURES USED IN CLINICAL SETTING

| *Object (concept)* | *Operationalization* | *Measure* | *Instrument* |
|---|---|---|---|
| **Trait Sleepiness** Introspective | Propensity to fall asleep in everyday situations (varied levels of stimulation) | Subjective Self-reporting Retrospective | ESS Scale: 0-24 Abnormal: >10 |
| **State Sleepiness /Alertness** Introspective | Current level of conscious | Subjective Self-reporting | SSS Scale: 1-7 Abnormal: >3 |
| **Trait Sleepiness** Introspective | Sleep patterns for 1-2 weeks | Subjective<br>Objective | Sleep log (1-2 weeks)<br>Actigraphy |
| **State/Trait sleepiness** Physiologic | Ability to fall asleep (time to fall asleep in a soporific environment) | Objective | MSLT Scale: 0-20 Abnormal: < 5 min |
| **State/Trait Alertness** Physiologic | Ability to stay awake in a soporific environment | Objective | MWT |

### D. Utilization of Measures

The objective measures, such as MSLT or MWT, are expensive and time consuming. Typically, they are used in cases of narcolepsy and unexplained sleepiness. The sleep clinics use almost exclusively the Epworth Sleepiness Scale for evaluation of excessive daytime somnolence. ESS is also recommended by the British Columbia Medical Association for the OSA pre-assessment and screening in family practice.

### E. Severity of Sleepiness

The International Classification of Sleep Disorders defines the severity of sleepiness as *mild, moderate,* and *severe*. These degrees are defined in subjective terms of impairment of social functions and work. For example, severe sleepiness is defined [2] as "Sleep episodes are present daily or during times requiring mild to moderate attention. There is marked impairment of social or work function.".

### E. Semiotic framework for sleepiness

Sleepiness can be represented as a set of objects (concepts) $O_s$ = {*trait introspective, state introspective, trait physiologic, state physiologic*}, the possible measures are represented by a set $M_i$ = {*subjective restrospective, subjective, objective*} and a set $U_s$ of utilizations. Utilization is defined as a tuple <*instrument, type, range,* $\mu_i$ >, where $\mu_i$ is a set of membership functions for sleepiness grading.

Fig. 2 illustrates semiotic representation for the trait introspective sleepiness measured by the subjective retrospective Epworth Sleepiness Scale.

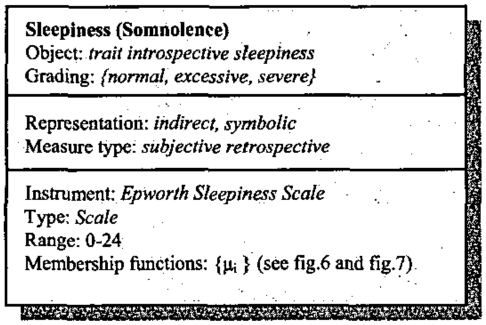


Fig.2 An example of the semiotic framework for sleepiness

## III. THE FUZZY LOGIC FRAMEWORK

A Fuzzy Inference System (using MATLAB) was developed by the authors for estimating OSA risks. The input, output variables and rules were constructed based upon experts' knowledge from three sleep disorders clinics and existing sleep medicine literature. The following diagnostic rule (R1) is used here as an example [1]: "Snorers with excessive daytime sleepiness and high blood pressure are at risk for obstructive sleep apnea." This example uses three input variables: *Sleepiness*, *Snoring*, and *Blood pressure* as illustrated in Fig. 3.

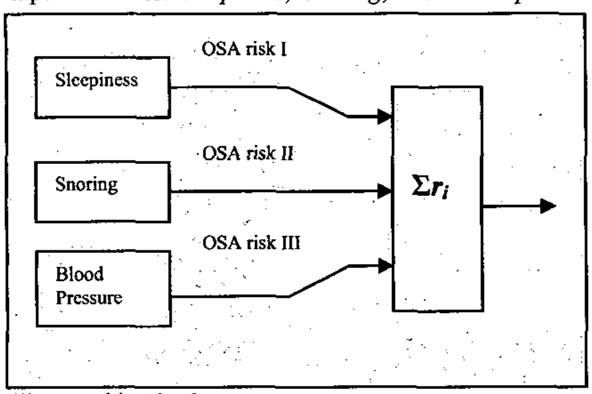


Fig.3 Fuzzy Inference System for OSA risks.;

The three input variables *Sleepiness*, *Snoring*, and *Blood pressure* illustrate the range of the three concepts with various accuracies of operationalizations. Sleepiness is not directly measurable and its subjective measure, ESS, introduces several biases. Snoring can be directly recorded as an acoustic signal and analyzed for specific patterns. On the other hand, snoring has also temporal quality and the 'habitual' snorers have higher risk for OSA. The blood pressure is directly measurable as an average systolic and diastolic pressure at rest [19,20].

### A. Membership Functions for Systolic Blood Pressure

The membership functions for systolic blood pressure are represented in Fig. 4. The *blood pressure* variable has the following terms: *low/normal, high normal, high, severe*. The low and normal systolic blood pressure are considered to be below 130 mmHg, the high normal between 130-139 mmHg, the high blood pressure between 140-179 mmHg, and the severe high is above 180 mmHg.

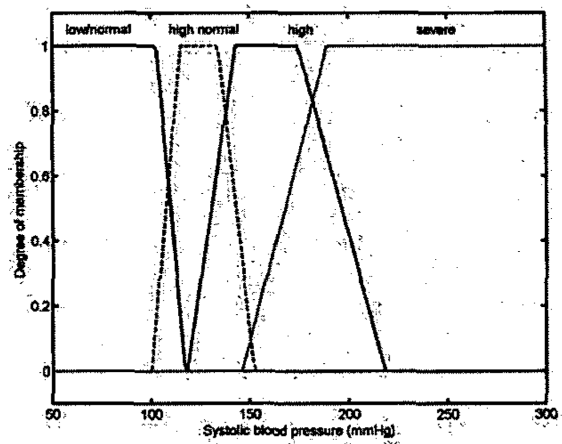


Fig .4 Membership functions for systolic blood pressure.

Fig. 5 represents the OSA risks for two variables: *Sleepiness* and *Blood pressure*. The risks are represented by an interval from 0 to 10. The high blood pressure and severe daytime sleepiness significantly change the risks.

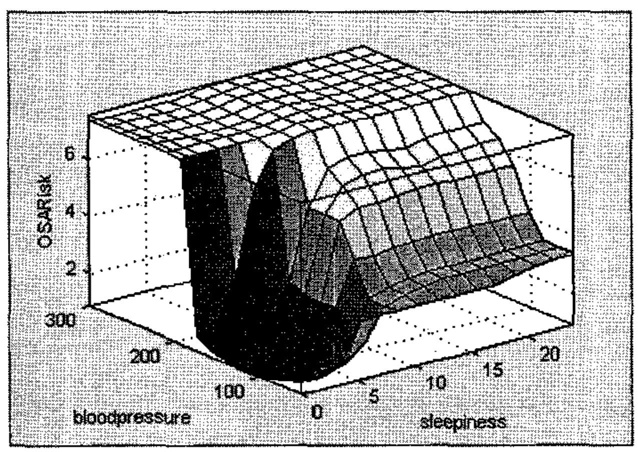


Fig. 5 OSA risks evaluated from Sleepiness and Systolic Blood Pressure.

### B. Membership Functions for Sleepiness: Reliability

The definition of the membership functions for the variable *Sleepiness* requires the analysis of *measuring reliability*, *validity*, and *systematic errors*.

This paper uses the following definitions for *measuring reliability* and *validity*:

1) *Reliability* is the degree to which a measure of the same object would produce the same values when repeated.
2) *Validity* is the degree to which a measure accurately represents the concept.

Assuming the existence of a 'true' value, the validity can be expressed as the difference between the actual measurement value $x_i$ and the true value $t_i$. The classical measure equation (1) for a true score involves the $e_i$ random error and $b_j$ the systematic (bias) error.

$$x_i = t_i + e_i + b_j \qquad (1)$$

The systematic error $b_j$ is usually caused by the characteristic of the studied subpopulations (gender, age, culture, profession). The subjective measure of sleepiness introduces several such biases.

### C. *Membership Functions for Sleepiness: Bias Analysis*

Several studies [21,22,23,24] demonstrate that the ESS results might be considerably biased by the following factors: 1) gender, 2) medical condition (depression), and 3) occupation (truck drivers or police officers).

The Multicenter Sleep Heart Health Study evaluated 6,440 participants (52% women) and reported that ESS is more likely to identify sleepiness among men than women [21]. Women tend to underreport their daytime sleepiness and, instead, report tiredness. The study of depressed patients [22] reported that the subjects overestimate their sleepiness. The study [24] of Italian police officers show that they significantly underreport their sleepiness and that the threshold for ESD should be lowered to score above 9.

The specific subpopulations require modified membership functions to reflect the systematic error of underestimation or overestimation.

Fig. 6 and Fig. 7 illustrate two sets of membership functions for the *normal*, *excessive*, and *severe* sleepiness in the general population and female population. The second set (Fig. 7) is constructed to compensate for the systematic underreporting of sleepiness among women.

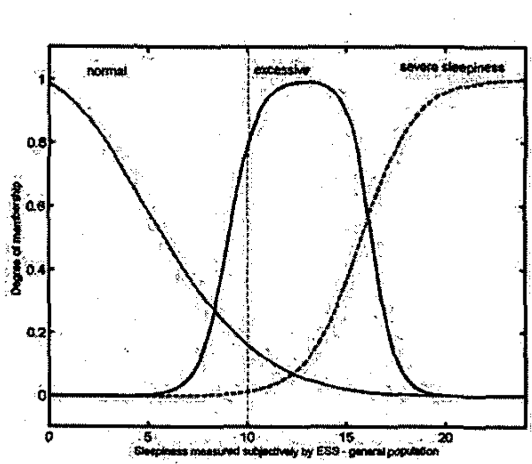


Fig. 6 Sleepiness in general population

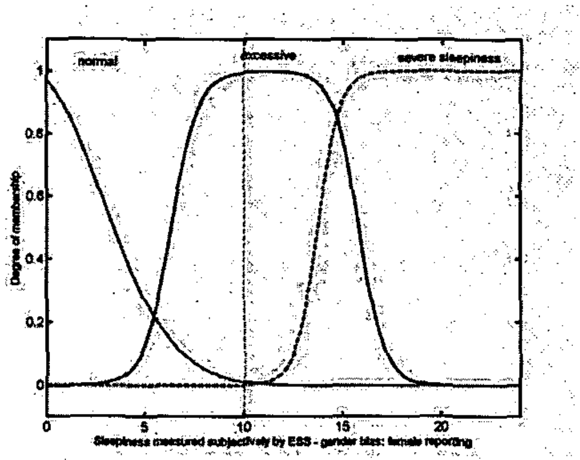


Fig. 7 Sleepiness biased by gender

## IV. SEMIO-FUZZY SYSTEM

The semio-fuzzy system for OSA risks analysis has two components: 1) Semiotic Knowledge Base (SKB) with a set of modularized Semiotic Filters (SF) that modify the membership functions based on additional patient's information (for example: gender, age, medical history), and 2) Fuzzy Inference System processing semio-fuzzy rules. The SKB includes the objects for all OSA risk factors, for example: sleepiness, snoring, blood pressure, morning headaches, and smoking. Semiotic filters are used selectively for risk evaluation in specific subpopulations.

Fig. 8 illustrates the semio-fuzzy system with semiotic filter SF1 for the evaluation of *Sleepiness* using a gender bias for the female population.

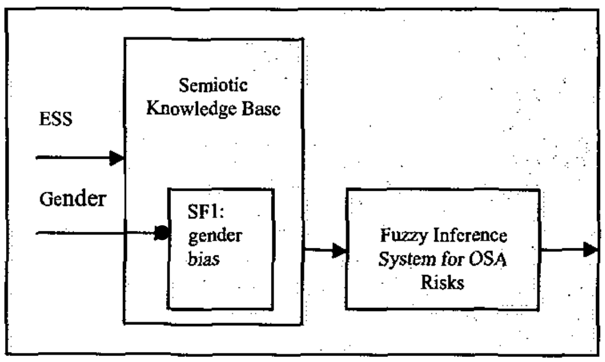


Fig . 8 Semio-fuzzy system with semiotic filter for gender bias

### A. *An Example of Semio-fuzzy Rule for OSA Risks*

The following fuzzy rule R1 uses three variables: *Snoring*, *Sleepiness*, and *Blood pressure*. It can be expressed as a traditional fuzzy rule:

**R1**: IF snoring is *habitual* AND sleepiness is *excessive*

AND Blood pressure is *high*
THEN OSA risk is *high.*

Using the semiotic knowledge base, the rule R1 is represented by a semiotic rule **SR1** (only the sleepiness is represented by a semiotic framework) and a semiotic filter (SF1) for the gender bias.

**SR1**: IF snoring is *habitual*
AND <object: trait introspective sleepiness
representation: indirect symbolic
measure: subjective retrospective
Instrument: ESS
(**SF1**: gender_bias ($\mu_i$) )>
IS *excessive*
AND Blood pressure is high
THEN OSA risk is *high*

## V. Conclusions and Future Work

This paper presents the initial findings of the issues related to the fusion of subjective and objective information in the diagnosis of obstructive sleep apnea. The membership functions used in semiotic filtering are based on sleep medicine literature and the consultations with two sleep experts Najib Ayas, MD, a sleep specialist from UBC and Les Matthews, coordinator of the sleep disorder clinic at UCC in Kamloops. The semio-fuzzy approach is used for the knowledge representation and inference engine in the telemedicine sleep assessment system Morpheus. The proposed model will be further validated using retrospectively data of 1,000 patients from UBC sleep disorder clinic.

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