CAALYX: Evidence-based selection of health sensors for elderly telemonitoring

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Abstract— **The objective of the CAALYX project (Complete Ambient Assisted Living Experiment - funded by the Commission of the European Union) is to develop a telemonitoring system capable of detecting health alterations and falls in the elderly – at home and outside the home– and to alert the assistance services when necessary. Unfortunately, health disorders in the elderly often occur in latent or atypical ways; therefore, health telemonitoring in the elderly is both a medical and technological challenge. The choice of suitable physiological parameters to be monitored is thus the key to system optimization and to minimization of false negative and false positive reports.** Methods **This multi-step method is aimed at facilitating selection of the most helpful group of sensors for the diagnosis of the most relevant health disorders in the elderly. (i) Identification of frequent health disorders: using the Spanish national surveillance system for hospital data (CMBD - 2005) and the databases held by the emergency services of the Hospital Clínic de Barcelona and the Hospital de Mataró (Barcelona). (ii) Selection of relevant health disorders: since frequent health disorders have varying degrees of importance, a discussion group composed of independent physician experts was designed to establish priorities for health disorders to be monitored. (iii) Identification of physiological parameters: four geriatricians reviewed 1,200 bibliographical sources in order to identify the most sensitive and specific physical manifestations for the diagnosis of the previously selected health disorders. (iv) Sensor selection: the list of the most suitable physiological parameters for the diagnosis of health disorders was reviewed by a mixed group of experts (medical-technological) in order to choose parameters that can be measured using currently technology.** Results: **The physiological parameters finally selected are useful to detect frequent causes of decompensation in elderly persons, as well as to control chronic pathologies.**

Manuscript received January 12, 2008. The CAALYX project is funded by the Commission of the European Union as part of its Sixth Framework Programme (IST-2005-045215).

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I. Introduction

During senility, people gradually lose more and more functional abilities as they approach the last years of life.[1]

The consequences of functional loss are first evidenced in the most complex activities of daily life, such as working or driving (Advanced Activities of Daily Life – AADL) and progress to involve the most basic activities necessary for independent daily life, e.g. walking, dressing up or using the toilet (Basic Activities of Daily Life – BADL).

As functional impairment progresses, individuals need more assistance to help them complete these activities. Eventually BADL become impaired and self-care is no longer possible.

Functional loss in elderly people is accelerated by the onset of new diseases or decompensation of chronic ones.[2] Functional impairment is more severe and harder to revert if the causing disease or decompensation is not treated soon. Therefore, early detection of new health alterations and monitorization of chronic pathologies to prevent decompensation, are essential in elderly people at risk of dependence (frail elders).[3]

The CAALYX (Complete Ambient Assisted Living Experiment) system is focused on improving clinical control of chronic pathologies in frail elders, as well as on early detection of new health-related events.[4] We postulate that this system can prolong elderly persons' autonomy and self-confidence to live independently, thus reducing the social costs of dependence and institutionalization.

Unfortunately, early detection of health-related events in frail elders is not easy. Their organisms have a much reduced response capacity to stressing agents and their physiological responses are much weaker than those of younger persons. This situation hinders detection of adverse health conditions.[5] For example, frequent physical signs of pneumonia like fever or cough, may be absent in frail elders suffering from this disease.

Besides being weak, elderly persons' responses to disease may be atypical. The organs of an elder have a more reduced functional reserve than the organs of a young person. However, functional reserves are not equally impaired in the different organs; some organs are especially sensitive to decompensation e.g. the brain or the locomotory system. Since some organs "fail" before others, diseases affecting a different body area may be first evidenced as brain or locomotory impairment.[5] In the above example, pneumonia (affecting the lungs) may be manifested as disorientation or functional impairment or it may produce a fall. This is known as "atypical presentation of disease" and makes diagnosis in the elderly population

even harder. Since diseases present differently in older than in younger persons any system aimed at monitoring elderly persons must be specifically designed for this population group.

Unfortunately, pathologies affecting the elders and their manifestations have not been as studied as those affecting young people; consequently, not all of the necessary data for designing a system aimed at monitoring elderly people are available. Medical research presented in this paper is focused on widening our medical knowledge in relation to the major question that need to be answered for the CAALYX project: What are the most useful physical signs for diagnosis of the diseases affecting elderly people?

II. METHODS

During the diagnosis process, geriatricians handle a huge amount of data, which are completely excessive for an automated system. A system like CAALYX cannot measure more than a few physiological parameters out of the huge amount of existing ones. Thus, a clinically useful system requires optimal selection of relevant parameters which support the different diagnosis in elderly persons. For selection of the physiological parameters to be measured, we designed a research study in several steps (see figure 1).

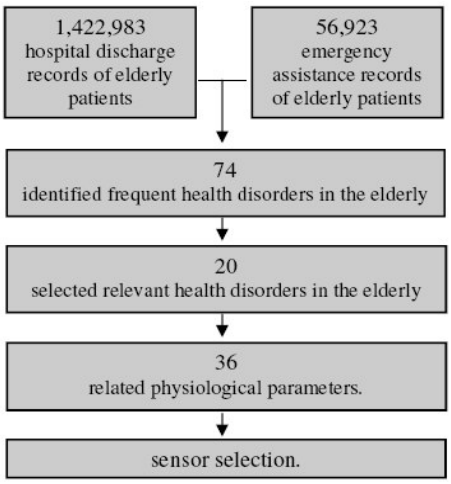

Figure 1 - Process step by step

Fist of all we identified the most frequent diseases affecting elderly persons upon visit to the emergency department or admission to hospital using the Spanish national surveillance system for hospital data (CMBD - 2005) and the databases held by the emergency services of the Hospital Clínic de Barcelona and the Hospital de Mataró (Barcelona). Secondly, since frequent health disorders have varying degrees of importance, a discussion group composed of independent physician experts was designed to establish priorities for health disorders to be monitored. Afterwards, the physiological parameters related to these relevant and frequent diseases were identified (more than 1200 bibliographical sources were reviewed). Lastly the physiological parameters associated to several of the relevant diseases were reviewed by a mixed group of experts (medical-technological) in order to choose parameters that can be measured using currently technology. At the end we came up with a list of measurable physiological parameters associated to frequent and relevant diseases in the elderly. Finally, we selected all of the parameters that could be altered by 4 or more diseases out of the relevant diseases group.

A. Selection of most frequent diseases

First of all, selected physiological parameters must be associated to the most frequent diseases affecting elderly persons upon visit to the emergency department or admission to hospital. In order to identify such diseases, we conducted a retrospective study.

This study included several Spanish hospitals. Eligible hospitals had computerized databases including information about the patients visiting the emergency department, collected for at least one year. Databases had to include at least the chief complaint for the emergency department or the coded diagnosis upon discharge and the age of patients. We preferred databases including information about the patients' sex and encrypted personal identification number, in order to identify repeated visits by a same patient. We handled no personal identification information so as to preserve patients' privacy.

We had access to 5 databases: Clinical Hospital of Barcelona, Hospital of Mataró (Barcelona), Santa Caterina Hospital of Girona, Hospital of Granollers (Barcelona) and Reina Sofía General University Hospital (Murcia). We evaluated the quality of their databases in terms of recorded number of patients, data collection period, quality of diagnosis codification, available additional information and amount of lost data. Finally, we selected the databases of the Clinical Hospital of Barcelona and the Hospital of Mataró. The total number of patients visiting the emergency departments recorded on both databases was 56,923.

We also accessed the Minimum Basic Data Set (MBDS) from the National Surveillance System for Hospital Data, corresponding to year 2005, which includes records of all diagnosis upon discharge from all Spanish public hospitals (97% of all Spanish hospitals). This database was used as a control to avoid unadvertised omission of any frequent cause of hospital admission.

We analyzed the frequency of the different chief complaints for elders (older than 64 years old) hospital visit in every database. In the Hospital of Mataró database, we additionally analyzed most frequent chief complaints in relation to age, time of the day and season. In the Clinical Hospital database, we analyzed the frequency of complaints in relation to sex and age as well as the most frequent complaints for repeated hospital visits. In the MBDS we analyzed the most frequent diagnosis upon discharge from hospital and their distributions according to sex and age. Finally, the frequency data from both emergency department databases (Clinical Hospital and Hospital of Mataró) were compared processed and pooled in order to produce a unique list containing the 74 most frequent diseases detected in elderly persons visiting the emergency department. The list of the 74 most frequent

diseases was examined by an expert group to establish priorities (next step)

B. Selection of most relevant diseases

A discussion group composed of independent physician experts was designed to establish priorities for health disorders to be monitored (among those identified in the previous step). Discussion was focused on the purpose of the CAALYX project, particularly on the specific objective of this meeting: namely, identifying diseases, pathologies or conditions that should be given priority in the use of technological monitoring solutions, such as the proposed in the CAALYX project.

Nine physicians – four female and five male – participated in this meeting. The group included only younger-than-55-years physicians, all with a minimum of seven years experience in medical services.

In regards to the heterogeneity criteria, it was not possible to count on a wider variety of specialists, in particular neurologists, pneumologists and emergency services; therefore, general medicine physicians (family doctors, geriatrists and internists) were overrepresented as compared to the initially expected. However, we counted on a well-represented variety of medical service levels: primary services, public hospital, private hospital, regional hospital and reference hospital.

In regards to the exclusion criteria, we changed the requisite of "not having met before", to "not having worked together before". Furthermore, two exceptions occurred to the criterion of "not holding a management / direction position": the representative of the emergency services and a second participant, who came in unexpectedly; he had been contacted though not formally invited, due to a communication breakdown. He was admitted to the group because not doing so was judged to be more disruptive for the group dynamics. This participant was a department director at a Primary-care centre. The meeting lasted for two hours.

In regards to their specialties and professional activities, participants were:

- Five family doctors, one of them also a geriatrician and one of them working as a department director in a Primary-care centre.
- Three geriatricians, one of them working as an internist in a private hospital, one specialized in home medical services, owner of a Day-medical centre for elderly persons and one working at a Public hospital.
- One physician working as the Emergency Service director at a Reference hospital.
- One cardiologist working at a Regional hospital and at his private medical offices.

C. Identification of physiological parameters associated to frequent and relevant diseases

Diseases present with signs and symptoms. Signs are the physical expression of disease and can be measured by an observer, e.g. high heart-rate (tachycardia) or high respiratory-rate (tachypnea). Symptoms are subjective expressions of the disease, which can be only perceived by the subject, e.g. pain or shortness of breath (dyspnea). Thus, signs are the only disease manifestations that can be measured with sensors, without the need of communication with the subject. Conversely, symptoms require participation of the subject, who has to communicate about them. The CAALYX system includes several ways for a caretaker or a physician to communicate with the user in order to detect symptoms (video-conference, mobile phone, questionnaires....); however, the goal of this part of the research was to select physiological parameters to be measured with sensors. Due to the fact that abundant information about physical manifestations of the diseases is currently available in the literature, we conducted this part of the research as a literature review.

Four Geriatricians, who had been previously trained, reviewed a number of bibliographic sources in order to establish a list of physical signs for every target disease. The target diseases were considered those previously selected by the discussion group (table 2), and 9 more selected by the researchers (influenza, gastroenteritis, urinary retention, pancreatitis, glucidic metabolism alterations, bowel bleeding, bowel obstruction, anaemia and kidney failure). We used Geriatrics and Internal Medicine treatises and journals indexed in MEDLINE consulted through the PubMed search service of the U.S. National Library of Medicine and the National Institutes of Health.[6,7] Every physician reviewed the literature independently. Every target disease was analyzed by at least two of them. The reviewed bibliographic sources were stored in a shared database.

D. Selection of the final sensors set

Developing a telemonitoring system to measure all of the physical signs that a physician measures during patient examination is not currently feasible. In this project we focus on measuring a group of physiological parameters associated to several of the relevant diseases, which can be measured with sensors currently available in the market. A group of medical-technological experts analyzed the physiological parameters associated to target diseases (previously selected), in order to identify those parameters that can be measured with currently available sensors.

Subsequently, on the basis of the above described literature review, we counted the number of relevant diseases altering each one of the proposed parameters. A preference order was then established by prioritizing physiological parameters altered by a larger amount of diseases. Finally, we selected all of the parameters that could be altered by 4 or more diseases out of the relevant diseases group.

Some of the target diseases present atypically, with physical signs that are rare in other diseases; thus, the most common physiological parameters are not useful to diagnose them. To avoid exclusion of relevant diseases that share few signs with others, two Geriatricians identified in our list those pathologies which present very few of the previously selected signs and proposed additional relevant physical signs or the use of alternative diagnosis systems.

III. RESULTS

A. Selection of most frequent diseases

The most frequent complaints for the emergency department (data from the Clinical Hospital and the Hospital of Mataró) and causes of hospital admission (MBDS) among Spanish elderly persons were: cardiovascular disease, respiratory conditions, trauma, fractures and infections, especially respiratory and urinary infections (see table 1).

Emergency department visits	Hospital Admissions
Bruises	Heart Failure
C.O.P.D.	C.O.P.D.
Dispnea / respiratory failure	Osteoarthritis
Abdominal Pain	Pneumonia
Chest Pain	Femur neck fracture
Conjunctivitis / eye inflammations	Cholelithiasis
Urinary tract infection	Myocardial infarction
Febrile Syndrome	Cerebral arteries occlusion
Incisive wounds	Cardiac arrhythmias
Heart Failure	Other respiratory diseases

Table 1 – The 10 most frequent chief complains at the emergency department and the 10 most frequent causes of hospitalization in Spanish elder population

Decompensation of Chronic Obstructive Pulmonary Disease (COPD), haematuria and acute urine retention were most frequent in men, while femur-neck fracture was most frequent in women. Some causes of hospital admission were more frequent in some age groups than in others. Hip fracture is among the first three causes of hospitalization from the age of 80 and it is the first cause from the age of 95. However, there are twenty further hospitalization causes for elders younger than 75. Urinary tract infections, wounds and bruises were more frequent causes for hospital visits in summer than in winter. Conversely, respiratory conditions were more frequent in winter than in summer; subtle differences were also found depending on the time of the day. A final list of the 74 most frequent complaints and diseases for hospital visit was prepared. These diseases account for 72% of total emergency visits.

In short, cardiovascular disease, respiratory conditions, infections and trauma were some of the most frequent causes for visiting the emergency department or for hospital admission in elderly persons. The list of the 74 most frequent diseases was used in the following steps of this research.

B. Selection of most relevant diseases. Expert group meeting.

Making it clear that the age of the target population is a necessary datum that has not been provided from the beginning, the group offered a preliminary list of situations relevant from the "health benefits" point of view: preventing fractures in the elderly, preventing decompensation in persons suffering from heart failure, preventing decompensation in persons suffering from COPD, brain-vascular disorders, preventing children's accidents, preventing prostate cancer, preventing rectum cancer. Children's accidents were mentioned only once; we interpreted this mention as a reference deliberately out of the scope of the discussion, intended for the chairwoman to delimit the question. Participants were then requested to rank the pathologies on the previously emailed list, bearing in mind that older-than-64 persons are the target population (the list included the 74 most frequent complains and diseases, prepared in the previous step). They selected several relevant pathologies (stroke, heart attack, COPD) and tried a ranking. At this point, participants turned to somehow taxonomical criteria in an attempt to rank the items on the proposed list, which seemed to cause them confusion or even discomfort. They first tried to make a "correct list" as a prerequisite for any further discussion or decision making (namely, before facing the task of "selecting" pathologies from the list, as proposed by the chairwoman). In order to rank the items on the list, they proposed to cluster the entities into the following areas or packs:

- Hearth disease, ischemic disease, effort angina, tachycardia, heart attack, cardiac failure.
- Respiratory
- Neurological entities
- Fractures, contusions
- Anxiety and depression

As one participant came in – almost one and a half hours after the start of the meeting – she added oedema to the pathologies indicated by the group, on the basis of its frequency and difficulty to diagnose. However, her suggestion was not generally agreed and remained as an individual observation.

Cluster	Disease
R	Dyspnoea And Respiratory Failure
NS	Fever
C	Heart Failure
N	Stroke, Brain Haemorrhage, Tia
R	Lower Respiratory Tract Infection, Acute Bronchitis
T	Femur Fracture
C	Auricular Flutter And Fibrilation
PS	Anxiety / Depression
T	Epigastralgia
PS	Acute Psychotic Episodes
C	Ischemic Cardiopathy

Table 2 - List of the most relevant pathologies. R: respiratory disease, C: cardiovascular disease, NS: non specified, N: neurological disease, T: traumatologic disease, PS: psychiatric disease.

After the classification effort, the chairwoman introduced a question aimed at re-focusing the group's attention on pathology ranking through a radical approach, namely, she asked the participants to choose only one most relevant disease/pathology. The first mentioned answer was **stroke**, immediately agreed by the rest of the group. Consensus

about the relevance of this pathology was maintained throughout the meeting. Two further pathologies were proposed for the ranking: aspects that produce the psychical ailments **anxiety and depression** and cardiorespiratory diseases.

The different criteria the group handled in order to rank the different pathologies included prevalence/target population size, relevance/significance, reversibility, preventing damages, severity of sequelae and preventing admissions or readmissions. The priority diseases established by the group are shown in Table number 2.

The thematic analysis was complemented by a frequency analysis of the main concepts in the group's discourse (table 3)

Health disorder	Freq.	Aggregate
Cardiac	71	71
Stroke	51	51
Respiratory/lungs	42+4	46
Cardiorespiratory Failure	20	20
Cardiovascular	8	8
COPD	5	5
Neurological	8	8
Psychological/mental	5+3	8

Table 3 – Number of times that a concept was mentioned.

C. Identification of physiological parameters associated to frequent and relevant diseases

We reviewed a total of 1200 bibliographic sources. Thirty four relevant physiological parameters associated to the previously selected relevant diseases were identified (the main ones shown in table 4).

Main hysiological parameters or disease manifestations	
Heart Rhythm	Bowel pattern
Heart electrical activity	Urinary frequency
Blood Pressure	Urine sediment
Temperature	Functionality for ADL
Respiratory rate	Glycemia
Blood oxygen saturation	Alertners / Consciousness
Cough / Productiveness	Alcohol / Toxic levels
Body weight	Speech characteristics
Gait parameters and falls	Hydratation and perfusion
Sleep parameters	Fecal blood

Table 4 - Relevant physiological parameters

D. Selection of the final sensors set

We eliminated the following parameters from our list, because measuring them was not feasible within the scope of the CAALYX project: alterations in skin and mucosal colour, alterations in skin and mucosal hydration status, tremor, perfusion alterations, changes in body perimeters, cardiac output, signs detectable upon auscultation, jugular engorgement and alterations in pulse characteristics. The rest of parameters are shown in Table 5 according to the preference order (according to the number of diseases that alter them). We finally selected those parameters, which can be altered by 4 or more target diseases.

Physiological parameter	Number of target diseases affected
Heart ratio	14
Functional impairment	10
Respiratory rate	9
Sleep disorders	7
Blood oxygen saturation	6
Nausea and vomiting	6
Urinary frequency and volume	5
Temperature	5
Blood pressure	4
Weight changes	4
Bowel rhythm	4
Urinary sediment	4
Falls	4
Cough	3
ECG	2
Mussel strength	2
Gait, balance, mobility	2

Table 5 - Physiological parameters related to the target diseases, according to preference order.

A review of the diseases list evidenced that the selected physiological parameters were not useful to diagnose depression, mild stroke and alterations in bowel movements or to control diabetes. Consequently, inclusion of a glucose measuring device and periodical questionnaires designed to monitor depression and alterations in bowel movements were proposed. Additionally, inclusion of questionnaires aimed at monitoring other physical signs in the list, such as urination frequency, sleep disorders and changes in functional ability, was agreed. Finally, we considered that information about motility and physical activity was essential for interpretation of the heart-rate, respiratory-rate and blood pressure data.

Physiological parameter	Detection method	Frequency
Heart rate	Sensor	Continuously / tree times a day
Functional impairment	Questionnaire	Monthly
Respiratory rate	Sensor	Continuously / tree times a day
Sleep disorders	Questionnaire	Weekly
Blood oxygen saturation	Sensor	Several times a day / daily
Urinary frequency	Questionnaire	Weekly
Temperature	Sensor	Continuously / tree times a day
Blood pressure	Sensor	Daily / weekly
Weight changes	Sensor	Weekly / monthly
Bowel rhythm	Questionnaire	Weekly
ECG (other than heart rate)	Sensor	Monthly
Mobility / Falls	Sensor	Continuously
Glycaemia	Sensor	Daily / weekly
GPS location	Sensor	Continuously
Depression	Questionnaire	Every tree months

Table 6 - Physiological parameters recommended for CAALYX, and preferred detection method.

Table 6 shows the final list of signs and symptoms recommended to be routinely measured by the CAALYX system, either by using sensors or questionnaires. Table 6 also shows recommended measurement frequencies for each parameter; these frequencies are approximate and depend on the nature of the involved parameter; furthermore, they should be established individually for each user, according to his/her particular needs.

IV. Discussion

A number of monitoring systems are currently available for remote control of persons' health, including systems specifically designed for the control of certain chronic diseases [8]. However, the CAALYX system is probably the first system designed for monitoring the health of elderly people. As mentioned above, elders have physiological and physiopathological particularities, which result in disease presentation and frequency different from those of younger people.[5] Consequently, a monitoring system to be used in elderly people must have been specifically designed for this age group. The choice of parameters to be remotely monitored with these systems is often weakly substantiated or it is based on experts' opinions. Because of the particularities of the population to be monitored, we followed an objective procedure designed to select the most useful physiological parameters for elders' health follow-up care. From our point of view, this means added value for the CAALYX project; moreover, the results of this research might be applied to several other technological projects aimed at the elderly population.

The goal of this research was focused on identifying physiological parameters rather than specific sensors. Usability is central to the selection of sensors for the monitoring system; however, it is not as directly related to the measured physiological parameters as to the sensors (e.g. depending on the type of sensor, measurement of the heart rate may be obtrusive or non-obtrusive). Therefore, this paper is focused on the selection of physiological parameters; thus, the main aspects of CAALYX usability are not addressed here.

Noticeably – though not intended by the researchers – the physiological parameters selected on the basis of this research were coincident with those evaluated and recorded by geriatric nurses in routine care of patients, and used by physicians in their basic decision making. The fortunate coincidence between physiological parameters selected through objective procedures and those deriving from clinical experience, suggests that these are the most relevant vital signs for the control of elderly people's health. Since both our selected parameters and the most frequently used parameters in geriatric clinical practice were coincident, they were displayed with the appearance of hospital nursery records (to which physicians are very used) in the interface between the CAALYX system and the patient's physician (who has access to the information stored in the system).

Since the present study was based on data from Spanish hospitals and on the knowledge of Spanish experts, in principle, it is not generalizable to other European countries; this poses a limitation to the study. However, significant variations in results are not expected for other countries since the usual clinical practice – coincident with the results of this study – is widely generalized. The disease frequency study was retrospective, based on already existing data bases, which could bring about some inaccuracy. However, those data bases had been created for proposes very similar to those of the present study; furthermore, retrospective studies seem to be the only feasible way to carry out large-scale incidence studies. The opinion of experts groups is usually associated to poor scientific evidence too; however, this is the only way to assess non-quantifiable aspects such as the "relevance" of certain diseases. In order to minimize this limitation, the experts groups taking part in this study were carefully designed and evaluated through scientific methods of qualitative research.

Acknowledgment

We should like to thank Dr. Carles Miret Mas (Hospital de Mataró, Barcelona), Dr. Luis García Eroles (Consorci Sanitari del Maresme, Barcelona), Dr. Joan Manuel Salmerón Bargo (Hospital Clinic, Barcelona), Dr. Fernando San Eustaquio Tudanca (Hospital General Universitario Reina Sofía, Murcia) Dr. Enric Pedrol Clotet (Hospital General de Granollers, Barcelona), Dr. Jaume Heredia Quicios (Hospial de Santa Caterina, Girona) for their invaluable help in collecting frequency study data.

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