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A Knowledge-based Infrastructure for the Management of Diagnostic Imaging Procedures in the Heart Failure Domain

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Abstract. Within the European HEARTFAID Project, an integrated platform of services has been developed to assist chronic heart failure stakeholders in their routine workflow and to provide an optimal management of heart failure patients, by exploiting the most advanced technologies, innovative methods for diagnostic data processing, and significant and up-to-date knowledge, suitably formalized.

Since signal and imaging investigations are currently a basic step of the diagnostic, prognostic and follow-up processes of heart diseases, the platform has been designed so as to include an advanced system for the management, storage and deployment of the related heterogeneous information, ranging from the raw data –consisting in 1D signals, 2D/3D images and image sequences– to the extracted quantitative parameters and, finally, to their interpretation.

The purpose of this paper is to describe an effective way to obtain an integrated management of all the data and transactions across the distributed repositories necessary to deal with such workflows. Intelligent knowledge-based services are also provided for assisting –in a holistic approach– all the decision making processes related to those data.

In particular, among the several functionalities provided by HEARTFAID platform, the paper focuses on the integration of echocardiography workflows. To this end, a suitably developed standard-compliant IT infrastructure called *EchoCardio Lab* is introduced and architectural details of its components are given.

1 Introduction

Chronic Heart Failure (CHF) is a complex cardiovascular syndrome, very significant for incidence and prevalence, which would strong benefit from a suitably defined care management program, aimed at improving and personalizing health care by slowing down the progression of the disease, alleviating symptoms, reducing hospitalizations, and minimizing risk factors [1]. These benefits can be achieved by a complex clinical workflow that entails identifying, collecting, integrating and processing a huge, heterogeneous and distributed amount of biomedical data. Some attempts to cope with the problem of CHF patients' management have consisted in the development of dedicated IT solutions such as automated guidelines systems [2], decision support systems [3], or machine learning methods for automated HF diagnosis [4] or prognosis [5] (see also [6] for extensive bibliography).

Within the European STREP project HEARTFAID (www.heartfaid.org), an integrated platform of services is being developed for assisting CHF stakeholders, in particular clinicians and general practitioners, in their routine workflow and in providing an optimal management of CHF patients.

The platform has been designed by exploiting the most advanced and standard-compliant technologies, innovative methods for diagnostic data processing, and significant and up-to-date knowledge suitably formalized [7][8]. The main functionalities of the platform can be summarized as (i) patients' telemonitoring; (ii) timely and interactive access to patients' data; (iii) interpretation of diagnostic investigations; (iv) therapy planning. These mainly rely on the platform intelligence core represented by a Knowledge-based Clinical Decision Support System (CDSS) which has been developed by integrating, in functionally advanced settings, (i) deductive knowledge, elicited from guidelines and medical experts; (ii) inductive knowledge, extracted by data mining techniques applied to significant piles of data; (iii) computational methods for the analysis and interpretation of diagnostic data. The main goal of the system is to assist, at decisional level, the CHF health care operators, by making more effective and efficient all the processes related to diagnosis, prognosis, therapy and healthcare personalization of CHF patients [9].

Since signal and image investigations play a major role in the management of cardiovascular diseases, the integration of the clinical workflows centered on signal and imaging resources has been carefully considered in the design of the platform.

The main aim has been to provide an integrated environment covering all the steps involved in such workflows, starting with the data transfer from the diagnostic modality, going through reporting procedures and clinical findings interpretation and ending with the actual exploitation of the produced clinical documents.

In this paper, we primarily focus on the integration of echocardiography workflows. Indeed, among the various diagnostic resources relevant to CHF, echocardiography represents the key imaging modality and its management requires dealing with complex and heterogeneous data, ranging from the original 2D and

2D+1 imaging data, to computed numerical parameters, textual annotations and processed images. In addition, such information is created at multiple stages and is subjected to revision/approval procedures. Considering such issues, a specially designed infrastructure called *EchoCardio Lab* has been built for providing an integrated management of all the data and transactions related to echocardiography workflows. Since the HEARTFAID platform has been conceived as a flexible and adaptable system, capable to be plugged into different realities, also the *EchoCardio Lab* infrastructure has been designed in order to cope with different levels of Hospital Information Systems (HIS), by largely adopting clinical standards (especially DICOM [10] and HL7 [11]) and taking into account IHE integration profiles.

Besides being a complex and interoperable repository of heterogeneous data, the *EchoCardio Lab* provides smart functionalities for the interpretation of echocardiographic images and parameters. Thus, the infrastructure assists not only the mere data transactions, but also the decision making processes related to those data; clearly, this represents an innovative feature of the infrastructure and places the *EchoCardio Lab* among the systems for *intelligent data analysis* in medicine (see e.g. [12]). Indeed, such advanced functionalities are obtained by including in the infrastructure the suitable modules for CDSS and the computational models for image processing presented in [14].

The fruitfulness of the integration of Computer-Aided Diagnosis (CAD) methods with Picture Archiving and Communication System (PACS) has already been noticed e.g. in [13], in which a specific standard-compliant toolkit is presented for favoring the extensive use of CAD so as to achieve the maximum benefit within a clinical environment. The *EchoCardio Lab* goes further integrating in a modular architecture more extensive analytical and knowledge-based decision support services capable to assist –in a holistic approach– all the decision making processes related to echocardiography workflows.

The paper is organized as follows. First, the relevance of echocardiography for the practical management of CHF is discussed and basic echocardiography workflows are introduced in Section 2. In Section 3 the actual components of the *EchoCardio Lab* infrastructure are detailed while in Section 4 the deployment of the infrastructure is illustrated with a real use case and the achieved results are discussed. Section 5 ends the paper with some remarks for future work.

2 Echocardiography Workflows in Heart Failure

Nowadays echocardiography is a digital modality, offering the opportunity to coordinate its workflow in an IT framework. When considering echocardiography workflow, we are mainly interested in TransThoracic Echocardiography (TTE), for its versatility and portability and for its fundamental importance in the management of CHF patients. Indeed TTE is the single most useful diagnostic test in the evaluation of patients with heart failure and, coupled with Doppler flow studies, permits to determine whether abnormalities of myocardium, heart valves, or pericardium are present and which chambers are involved [15]. The most important measurement performed by TTE is the Left Ventricle (LV) Ejection Fraction (EF), which permits to distinguish patients with cardiac systolic dysfunction from patients with preserved systolic function. EF is given by the normalized (non-dimensional) difference between LV End-Diastolic Volume (EDV) and the End-Systolic volume (ESV). In addition, TTE provides other quantitative measurements relative to ventricular dimensions and/or volumes, wall thickness, chamber geometry and regional wall motion, and semi-quantitative rapid assessment of valvular function, especially of mitral, tricuspid and aortic stenosis and regurgitation. Some of these parameters allow obtaining good estimates of other clinically important quantities, such as systolic pulmonary artery pressure.

An echocardiography study thus generally consists not only of still images, but also contains image sequences, since some of the parameters estimated by TTE (like EF and regional wall motion) requires the analysis of the whole heart cycle. Besides digital images, an echocardiography study should be equipped with measurements and an interpretative report.

Images are obtained by a sonographer who may make preliminary measurements and observations. According to IHE [16], the over-reading physician must have access to all of this data in discrete, structured format to synthesize a final report.

In an echocardiography lab reached by HEARTFAID, it would be optimal to store the original images, the annotated ones and the final report to the integrated platform. However, the treatment of digital images, both original and annotated, poses several problems, due to the discrepancy between the ideal hospital (from an IT point of view) and the situation usually encountered in a real one.

In the ideal situation, the hospital is equipped with a HIS, a PACS dedicated to the cardiology department, and, finally, echocardiography devices are persistently connected to the hospital network. For a patient, pre-admitted and registered in the HIS before undergoing an echocardiographic examination, a visit is scheduled and demographics and procedure information (for example why the visit is required, which parameters should be estimated during examinations,. . .) are transmitted accurately to the echocardiography device. After the examination, images are securely stored to the PACS and can be displayed at any imaging workstation. Echocardiographic measurements, performed anywhere, are correctly associated and securely stored with the study as discrete, structured data that can be interpreted by another workstation and finally incorporated into a report. In particular, interoperability is guaranteed among HIS, PACS, echocardiography devices and various reporting workstations.

In a real-world example, instead, echocardiography devices are not connected to any network. Sometimes, a workstation –provided by the echocardiography device vendor and running proprietary software– is associated. This workstation has one (or several) storage units to setup a local picture archive for the echocardiographic lab. Although potentially connectable to the hospital or global network, the local archive often can export images only to physical devices. In most cases, luckily, images are exported according to DICOM standard. For what regards echocardiographic measurements and findings (usually printed to paper and inserted into a patients folder) cardiologists typically have to retype the information into a separate reporting system, since cross document sharing seems not to be feasible. Further, review of already annotated images is not possible, since annotation is made through the proprietary software running on the echocardiography device.

Given such a discrepancy between ideal and real world, the *EchoCardio Lab* infrastructure has been developed taking into account nowadays hospital IT structures, with a view towards the future that –as far as we can see– will resemble more and more the ideal situation described above.

In particular, it has deemed essential for the success and diffusion of the *EchoCardio Lab* to offer:

State of the art interoperability In this way, the *EchoCardio Lab* could easily be connected to an ideal hospital IT infrastructure, allowing for the exchange of images, measures, reports, demographics and procedural information directly from the HIS/PACS to the *EchoCardio Lab* and vice versa.

Customizable modules to solve IT infrastructure lacks In particular, this amounts to develop methods and interfaces for uploading echocardiographic images and quantitative parameters to the *EchoCardio Lab* and query/retrieve such heterogeneous information.

The rather obvious answer to these two issues has been to adhere to standards (namely DICOM and HL7) and integration profiles (provided by IHE). The methods offered by the standards, suitably inserted in *ad hoc* interfaces, allow for image uploading, query/retrieve and review of reports from any workstation, either in the case of IT infrastructure lacks, as shown in next sections.

3 The EchoCardio Lab Infrastructure

The developed architecture is shown in Figure 1. All its components are integrated by means of a *Middleware*, which serves for a loosely coupled and highly distributed integration infrastructure. This means that all the components communicate among each other by exchanging messages on suitably defined middleware channels. To this end, standard protocols and messaging have been implemented, using in particular technological tools like *Web Services*, Mirth integration engine [17] and HL7 adapters developed by us. A Web Portal integrates all the graphic user interfaces accessible by clinicians.

Starting from the left bottom of Figure 1, we have an Echocardiography System (GE Vivid 7 Pro) using DICOM standard communication and an *ad hoc* Adapter Program –developed by us– able to perform HTTP multipart connections. A Repository collecting echocardiographic parameters is connected via HL7. A CDSS, composed of a Knowledge Base and rules and an inference engine, is connected via Web Services. A DICOM-compliant Image Archive is used to store echocardiographic images. An Image Analysis and Viewer, connected via HTTP, is used to improve echocardiographic images processing. A Mail Server is also used in order to send automatic notifications to users.

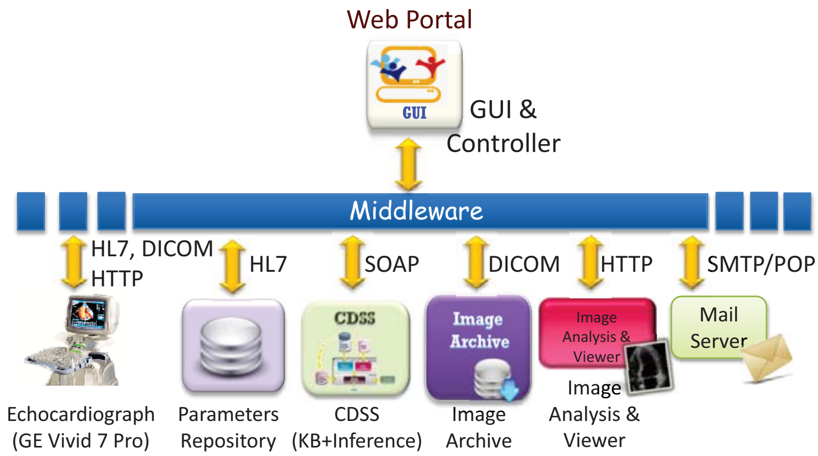

Fig. 1. Architecture of the *EchoCardio Lab* Infrastructure

3.1 Image Archive

After a careful analysis of end-user needs, it has immediately judged important to include in the infrastructure an *Image Archive*, capable to provide access/storage functionalities in an interoperable format. In particular, the following network interfaces to the Image Archive have been considered:

- DICOM network services for image transmissions and standard-compliant queries. This is the preferred way for interfacing with remote DICOM entities, such as hospital imaging modalities or PACS.
- Web Access to DICOM persistent Objects (WADO). This is a DICOM-compliant Web-based service for accessing and presenting DICOM persistent objects (e.g. images and reports), consisting in a simple mechanism for accessing a DICOM object from HTML pages or XML documents, through HTTP/HTTPs protocol.
- Web interfaces for Image Archive management and configuration (e.g. demographic data reconciliation, image study management and configuration of remote entities, users and groups).
- SQL access for low-level infrastructure management.

Among several open source implementation of DICOM, DCM4CHE [18] has been selected and employed. The Image Archive has also been setup to emulate DICOM Modality Performed Procedure Step (MPPS) for the configured echocardiography devices. In this way upon reception of new imaging data, a MPPS object is generated and stored in the Image Archive. In addition, such object is transformed into a HL7 ORM-O01 that is sent to the Middleware. The emission of other HL7 ADT messages related to patient demographics is also configured. In this way, the other components of the infrastructure are made aware in an interoperable way of changes in the Image Archive.

3.2 Image Analysis and Viewer Module

The search, retrieval, visualization and processing of the medical images stored into the Image Archive described in Section 3.1 are provided through the *Image Analysis and Viewer* module. The Web viewer interface provided by the module answers to the following needs of the *EchoCardio Lab* infrastructure:

- Reviewing of images by the referent physicians
- Reviewing of images for second opinion
- Quick access to image data (for example access to data of the previous examination in the same room where the new examination is carried out for appreciating changes in the clinical situation)
- Quick selection of images for post-processing analysis

The goal of the Web viewer interface is to give to physicians the opportunity to quickly access images and patient data stored in the DICOM Image Archive from anywhere by using a browser. The Viewer is constituted by the Web interface realized through the Java Server Pages (JSP) technology and a Java Servlet that manages the system workflow and the transactions with the Image Archive (performed, according to DICOM network services and, specifically, through the WADO services provided by the Image Archive itself). Through the interface, several types of search are provided; in particular, it allows easily retrieving the images relative to the studies of a patient by specifying the patient ID and –in order to obtain a more precise result– the study modality (UltraSound, Secondary Capture, etc.).

Once the study images are displayed, the system allows also downloading images and processing them in order to calculate the EF, EDV and ESV. Indeed, by selecting the *Process* button below the displayed image, the user may access the image processing module. The main goal of this module is to allow performing common linear, area and volumetric measurements on an image, directly inside the Web browser. Advanced assisted methods for the segmentation of ultrasound sequences –based on mimetic criteria and level set segmentation methods described in [19]– are also included; these methods provide the delineation of the left ventricle cavity in every frame of an apical image sequence, requiring a minimum of user interaction, as described in Section 4.1.

From a technological point of view, the image processing module is equipped with a custom Web interface (by using the JSP technology) and uses a Java

Servlet to manage the workflow and to interact with the DICOM Image Archive. In particular, the Servlet retrieves the image absolute path by directly querying the DICOM Image Archive via SQL; then, the Servlet calls the algorithms for image processing (developed in MATLAB language and encapsulated into Java classes); the resulting images and the computed values are displayed through the Web interface and, if the user accepts the result, they are stored into the Image Archive by exploiting a suitable Java class provided by the DCM4CHE toolkit [18].

3.3 Parameters Repository

The Web interface has been implemented using Java Server Faces in order to realize the Model-View-Controller pattern. The application server we have used is Sun Glassfish [20] and this allowed us using the Java Persistence API (JPA) [21] to handle data using the object-oriented paradigm. Among all the data handling steps, the fetching/storing and transformation cycles that required an accurate study have been i) the HL7 to Parameters Repository, ii) the Excel to Parameters Repository and the Parameters Repository to OWL (for this last point, see Section 3.4).

Starting from an echocardiography device, data is sent to *EchoCardio Lab* using HL7 or in the case of the GE Vivid 7 Pro using an Excel file and an *ad hoc* HTTP client built by us. In the first case HL7 is sent to a custom HL7 Java listener we developed. This listener then calls a Java module in order to bind received data to a set of JPA entities that are stored into the Parameters Repository, managed by PostgreSQL [22]. In the second case, the Excel file is parsed using a Java Excel parsing module; then extracted data is bound to a set of JPA entities that are stored into the Parameters Repository.

3.4 Clinical Decision Support System

The CDSS has been devised for processing patients' related information by exploiting the relevant medical knowledge opportunely elicited from medical experts and extracted from clinical guidelines, and suitably formalized into a symbolic, ontology- and rule-based *Knowledge Base* (KB). An *Inference Engine* is introduced in the *EchoCardio Lab* infrastructure for reasoning on the particular instances of the ontology according to the available rules codified in the KB. The results of such reasoning are suggestions to be presented to the final user.

From a technological point of view, the CDSS employs a suite of OWL [23] ontologies and Jena [24] rules. The provided functionalities are made available to the other components of the infrastructure by the use of *Web Services*. In particular, each time the CDSS is automatically called during the usual clinical workflow, a Java module is triggered to find required information in the Parameters Repository by using JPA fetching features and to transform these Java instances into OWL instances using a custom Java to OWL-binder. In this way our inference engine, Jena, is able to perform deductions using OWL classes and the so obtained OWL instances and the Jena rules.

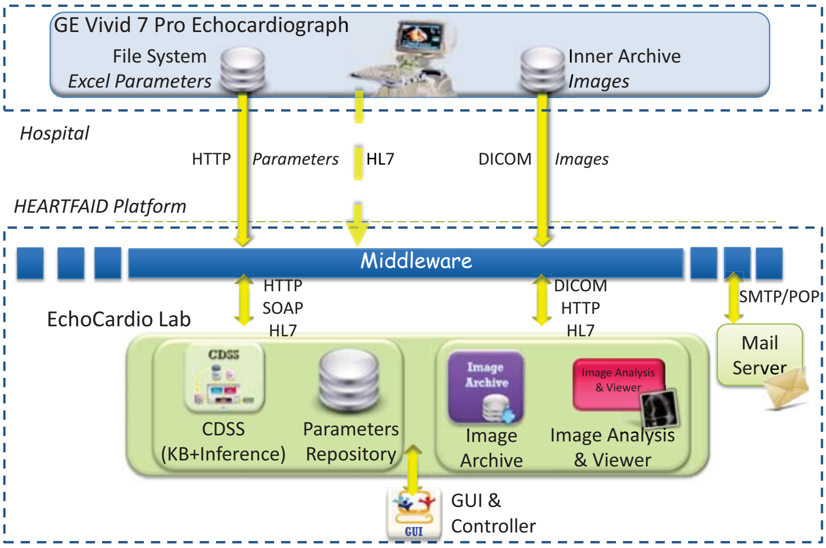

Fig. 2. Data flow and transactions among the components of the *EchoCardio Lab* infrastructure

3.5 Adapter Program

Besides developing a suitable HL7 listener to receive directly parameters data from echocardiographic devices, a custom *Adapter Program* has been developed to cope with some lacks of the GE Vivid 7 Pro echocardiography device, that has been used in the actual testing of the *EchoCardio Lab*. Actually, GE Vivid 7 Pro does not provide HL7 export features, but permits to export parameters in an Excel file to a local or remote shared directory. Aiming at providing direct parameters transfer in any case, GE Vivid 7 Pro functionalities have been extended by developing a C# Adapter Program we installed on the echocardiography system itself; the Adapter Program scans the directory where the Excel files are exported and –once discovered a new file– is able to send it to a Java Servlet using an HTTP multipart connection. This Java Servlet then parses the received file and stores the extracted data to the Parameters Repository by using JPA.

4 Deployment of the EchoCardio Lab infrastructure

Figure 2 shows in detail the main flows in the infrastructure, from which it is clear that the Middleware allows and manages the communication between the *EchoCardio Lab* and the Hospital. In this section we will describe an *EchoCardio Lab* use-case and we will discuss the achieved results.

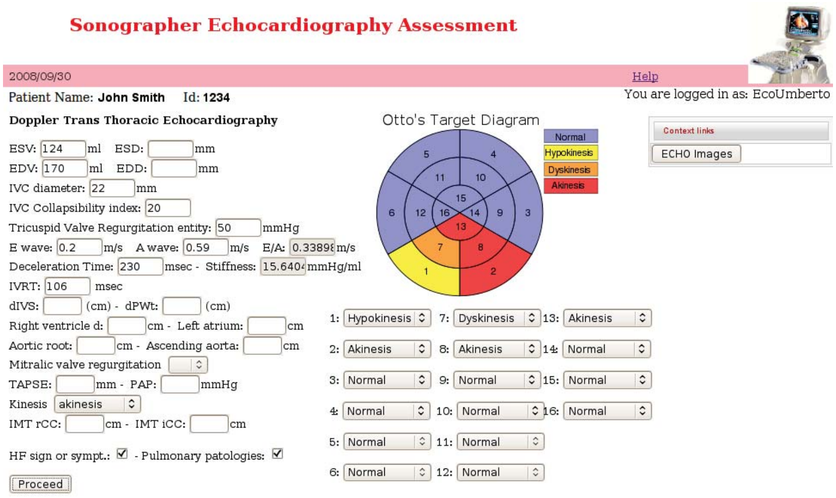

Fig. 3. Echocardiography Finalization

4.1 EchoCardio Lab Use-Case

A clinician logs in the *EchoCardio Lab* Web interface through the HEARTFAID Portal and he schedules a request for performing an echocardiography to a patient. A sonographer performs the scheduled echocardiography to the patient using a GE Vivid7 echocardiography device. At the end of the examination, images and parameters are automatically stored in an inner Database and also sent to the *EchoCardio Lab*. In particular, images are automatically sent to the Image Archive and are immediately accessible by the Image Analysis and Viewer module, allowing estimating again some critical parameters for a second opinion.

Parameters are also exported to a directory of the GE Vivid 7 filesystem as an Excel file. From there –through the Adapter Program and exploiting an HTTP multipart connection– information is automatically sent and stored into the Parameters Repository.

The clinician that scheduled the request of the echocardiography is automatically notified by email that the examination has been performed and that he has to finalize it. He then logs again into the *EchoCardio Lab* Web interface where he can see the list of the patients who have echocardiographies to be finalized. He selects the patient and the echocardiography to be finalized, and then he can browse the data sent by the Adapter Program. During the finalization (see Figure 3), the clinician may add other information and he may review the image sequences contained in the performed examination by clicking the top right *ECHO Images* button.

The Image Analysis and Viewer is thus called in the patient's context and the image sequences belonging to the selected study are shown. An image sequence can be viewed as still images or as a movie, by displaying the images in the

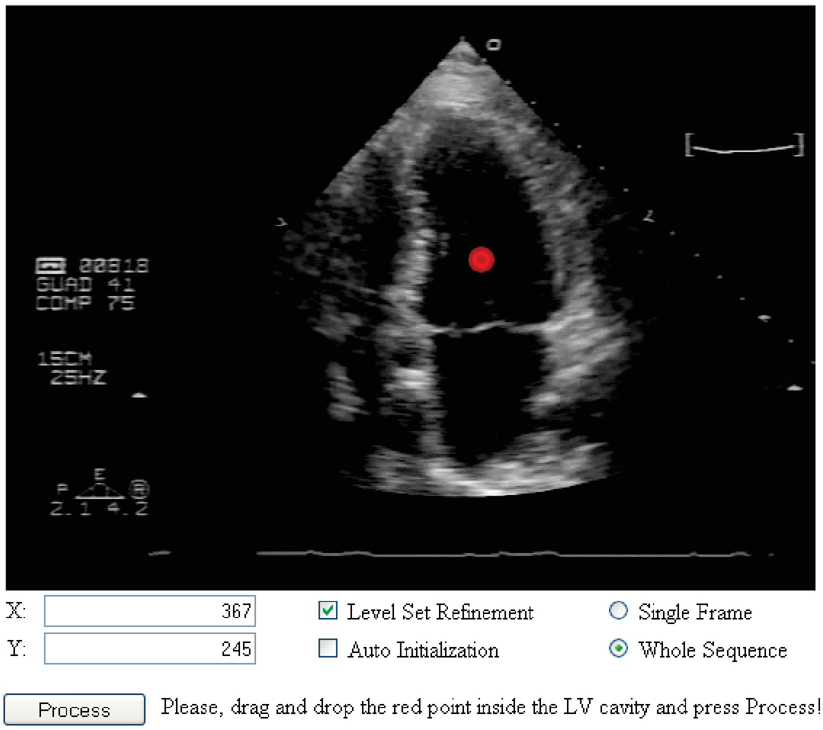

Fig. 4. Image processing step

sequence at an adjustable frame rate. The clinician can download the displayed DICOM image by clicking on the *DICOM Download* button. Instead, by clicking on the *Processing* button, the Image Processing page is accessed (as shown in Figure 4), by which the clinician is able to determine LV volumes and EF.

More in detail, the clinician may perform the assisted delineation of the LV border either in the displayed frame or throughout the whole image sequence by ticking the appropriate checkbox (*Single Frame* and *Whole Sequence* modes). A minimum of user interaction is required in both cases: the user should drag and drop a point inside the LV cavity in the displayed frame. Then, by pressing the *Process* button the image processing step starts.

Internally, the system calls the appropriate image processing methods. First of all, mimetic criteria are applied to find an approximation of the LV cavity boundary either on the displayed frame or throughout the whole sequence.

In the *Single Frame* mode, the system then refines the LV cavity boundary by applying a level set method for achieving contour regularization and better adherence to image edges. Using a method for the estimation of ventricular volumes based on Simpson's rule [25], the LV volume in the displayed frame is computed. Both the segmented image and the computed volume are presented to the user for approval.

In the *Whole Sequence* mode, the system computes the value of the ventricular volumes on the whole sequence, using the approximation provided by the mimetic criteria. Then a set of candidate systolic and diastolic frames is identified on the basis of the estimated volumes. The level set refinement is applied to frames belonging to this set and, after computing again ventricular volumes on the refined segmentation, the end-systolic frame and the end-diastolic frame are finally identified as the frames in which the minimum (resp. the maximum) of the volume are attained. Such segmented frames together with the computed ESV and EDV values are presented to the user for approval (as shown in Figure 5). In the meanwhile, the CDSS –automatically called– provides post-processed parameters and diagnosis as shown in the same figure. In both cases, the clinician can accept the result by clicking on the proper button. The new processed images are then stored into the Image Archive as a new DICOM Secondary Capture (SC) study of the patient while the computed values are stored into the Parameters Repository. After finalization, an HL7-ORU message containing the report information is emitted. Such message, besides being forwarded to external HL7 listeners, is transformed using XSLT to produce a human-readable final report of the echocardiography study, which is automatically sent to the referent clinician by email.

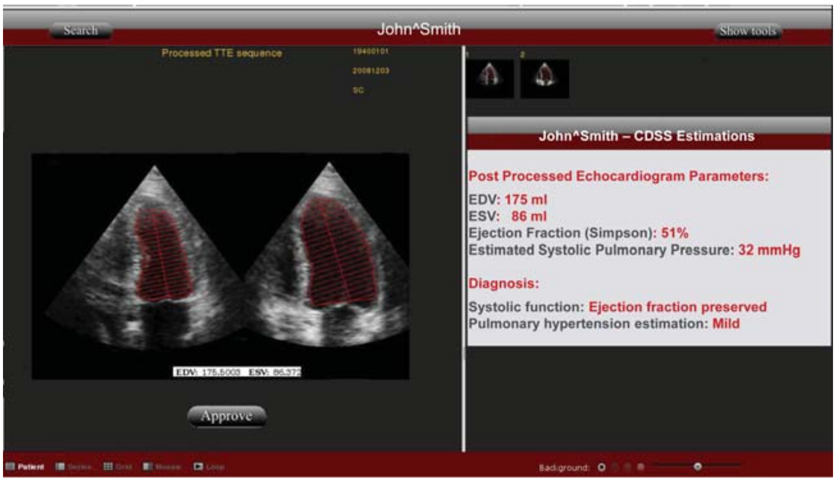

Fig. 5. Visualization of the processed images and key suggestions provided by the CDSS

4.2 Results and discussion

The *EchoCardio Lab* system is being evaluated at the Department of Cardiology, University Magna Graecia, Catanzaro, Italy. Participants to the study are patients admitted to cardiological visits for diagnosis and follow up of heart failure. In particular, 26 males (age 67.15 ± 13.40 years) and 6 females (age 78.5 ± 7.42 years) have been included up to now. Each patient has undergone from one to three echocardiographic examinations –accordingly to the normal workflow and clinical protocols. Each echocardiographic examination consists of about 20 images and image sequences, ranging from much focused examinations (consisting in 13 images) to full examinations (consisting in 32 images). Image sequences are acquired at the cine-rate of 25 fps and are stored as multiframe images. Generally, three heart cycles have been recorded in each image sequence, resulting in about 70 frames for each sequence. Both still images and frames have size 434×636 and are coded using the YBR_FULL_422 photometric interpretation. This image data is used to populate the Image Archive together with the derived data produced through the image analysis methods. The related patients' information and the echocardiographic examination reports have been also collected in the Parameters Repository.

The *EchoCardio Lab* has been tested with respect to i) reliability of the image analysis results, ii) correctness of the provided suggestions and iii) end users' satisfaction.

The first two kinds of test are more conventional. In particular, for testing the provided image analysis methods, the parameters computed by means of the assisted procedure have been compared to the parameters manually computed by the sonographers and found to correspond within the intra-observer variance. Quality of segmentation was also visually evaluated by expert observers. For the evaluation of the suggestion proposed by the CDSS, expert cardiologists have been asked to classify suggestions in *correct* or *non-correct*. After an initial stage in which some non-correct suggestions have been provided, the CDSS has been carefully revised taking into account its failures. After such revision, the CDSS has been found to provide only agreeable suggestions.

Besides correctness of the provided suggestions, the impact of the overall system on the routine workflows has been carefully taken into account, since this factor is deemed essential for its success. Such kind of evaluation is being done by performing several interviews with the clinical partners at different times (shortly after the introduction of the system and after 3 months up to now). The system has been perceived as non-invasive since its introduction, although some training has been necessary to make the medical personnel acquainted with the provided web interfaces. In particular, the suggestions provided by the CDSS are perceived as useful but not as intrusive, so representing –as desired– just *support* in the decisions the physician has to take.

In addition, the automation of the data transfer procedures (avoiding retyping and, thus, typos) and the easiness in accessing heterogeneous information has been particularly appreciated. The idea of preserving the patient's context –across interfaces dealing with multiple repositories– has been seen as a way to avoid time-consuming replicated search procedures throughout the Image Archive and Parameters Repository.

Thus, at least in the reality of the selected validation site, the system is contributing to a better delivery of care.

5 Conclusions

In this paper, we have presented the *EchoCardio Lab*, an infrastructure providing integrated management of all the data and transactions related to echocardiography workflows. In particular, the infrastructure guarantees retrieval, storage and deployment of heterogeneous data consisting in images and image sequences, clinical parameters and textual annotations across distributed repositories. Standard-based middleware functionalities are used for the communication among the components of the infrastructure and external ones (e.g. echocardiography devices), thus resulting in an extendable, adaptable and interoperable system. Decision support services and image analysis facilities are also introduced as advanced features of the infrastructure.

Future work will focus on a further improvement of the interoperability capabilities of the *EchoCardio Lab*. In particular, after a careful analysis of security and data sharing issues, cross-enterprise document sharing services will be introduced, so as to make the *EchoCardio Lab* usable among several hospital networks.

Acknowledgments

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