MESH GENERATION FOR GEOMETRIES IN BIOMECHANICS

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ABSTRACT –

In this work we show the features and difficulties encountered when we create meshes specifically for biomedical simulations. First of all, we describe the three differents types of geometry representation that we treat: boundary representation, medical images and tesselation. Secondly, we study how the generation of meshes is influenced by the problem, depending if it is a fluid or fluid-structure interaction case. Additionally, we show the dependence on the order of the elements (1st order or 2nd order) and the importance in the kind of sources (tessellation or CAD b-rep) that originated the geometries. Finally, we show FSI simulations of the ventricles of a human heart and LES simulations of the respiratory system; both solved with Alya the high order finite element code developed by Barcelona Supercomputing Center.

TECHNICAL PAPER –

1. GEOMETRIES FOR BIOMEDICAL APLICATIONS

In order to solve a computational simualtion, the first step is to obtain a realistic description of the geometry. How we can obtain an accurate geometry of a human organ is a really big question in computational biomechanics. There are three possible approches.

The boundary representation is one of the most common in engineering because we design what we will simulate. The CAD model in these cases it is an obligation. However, in biomechanics is exactly the opposite, we have a physical model that we want to reproduce in order to be able to simulate it. This counterside conduct us to the second option, medical images.

Medical images are a source of visual representations of the interior of a body which reveal internal structures, hidden by the skin and bones, by intensity of the pixels. They are the most realistic aproximation of the biomechanical systems. Nevertheless, isolating each part is not trivial. Although, currently, there are tools that automate the process, in the nearby of the boundaries between organs an expert should intervent. Even though, once the separation of the organs has been accomplished our discretization will be limited by the resolution of the image and, also, will be affected by staircase effect produced by the voxelization. If the resolution is good enough and we want to avoid the staircase effect, we should take a big enough number of points to generate a tesselation.

The last option, the tesselation, is a big simplification of the model, but even with the best medical images it is not possible to obtain the real geometry of the organs because they are always moving and changing. Hence, the tesselation it is acceptable way to obtain a geometry but without forgeting its limitation.

One approach is to use some points of the medical images to generate a boundary representation. Nonetheless, we are going to need even more points than with the tesselation and in the most cases we are going to introduce noise in the geometry. If we want to take this approach, the most common approximation, is to desing a model based on medical images. So, in the end we have more an artistic model than and real representation.

2. CHALLENGES IN MESH GENERATION FOR BIOMECHANICS

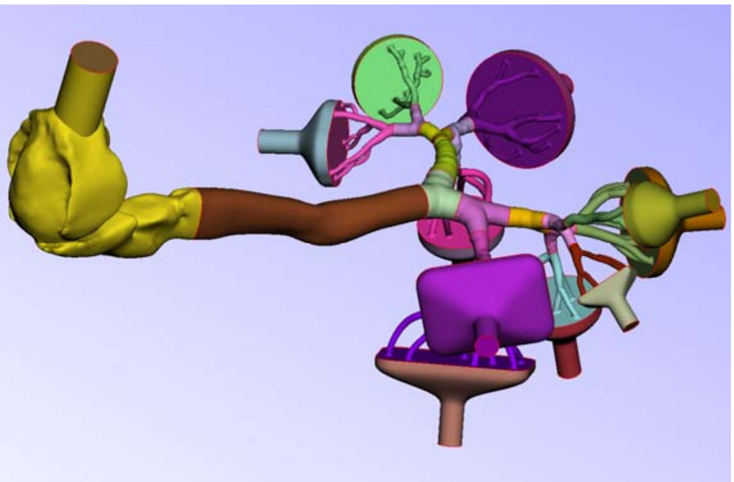
Giving general parameters to generate a mesh which guarantee a good quality is not simple because this will depend on the model, the type of geometry and the features of our simulation. Hence, we are given some advices using two differents models, with differents type of geometry and simulation.

On one hand, we will show the generation of a grid of a heart for a fluid-structure interaction, which model is a boundary representation. On the other hand, we had a tesselation (STL) of a respiratory system for which we created a mesh to run Large Eddy Simulation.

2.1 RESPIRATORY

In the case of the respiratory system, the geometry proceed from a moke-up where the interest is to evaluate the particles deposition. Hence, we want to contrast the results of the simulation and the experimental ones. Furthermore, we want to check the influence in the results of lineal elements and quadratic elements. Therefore, we had to obtain approximately the same number of nodes in each mesh to attain comparable results.

Once established the goals with this geometry we can create the mesh. First of all, we must check that model it is watertight. As you can see in Figure 1, it seems that exist gaps between the different parts of our geometry. This issue could be easily solved with connecting unconnected shell elements within a tolerance and describing iterations parametrically . Thereupon, we get a watertight model as shown in Figure 2.



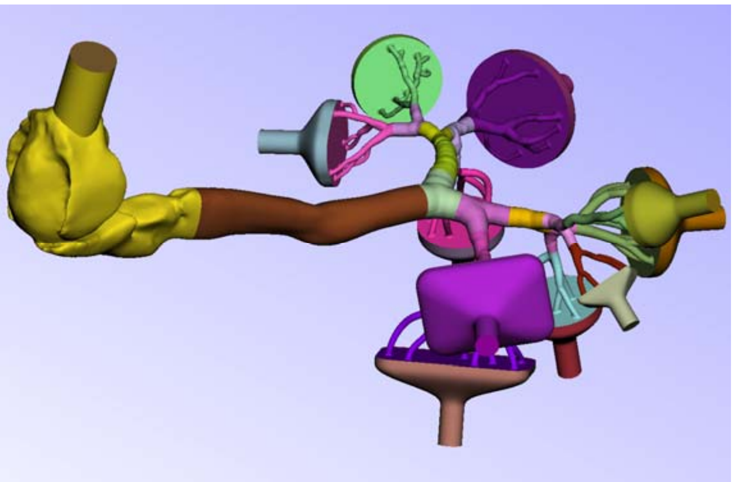


Figure 2 – Model watertight.

After this, we are ready to create a closed and clean surface mesh. Starting from shell elements which require local control of the mesh for feature line and curvature capturing. A good surface mesh it is mandatory to obtain a decent volume mesh.

Generate a volume mesh with lineal elements is straight forward, so we will explain how generate a quadratic mesh from this lineal surface. Firstly, we need to add extra nodes in the middle of the edges (Figure 3). However, this is not enough because we need a similar number of nodes as the linear mesh. To reduce the node number we need to recontruct the surface which also allows us to take avantange of the two benefits quadratic elements have: their shape function and its better matched of the geometry. So, the solution is to recontruct the surface with a target length that is to be the double of the original. The result it is shown in the Figure 4.

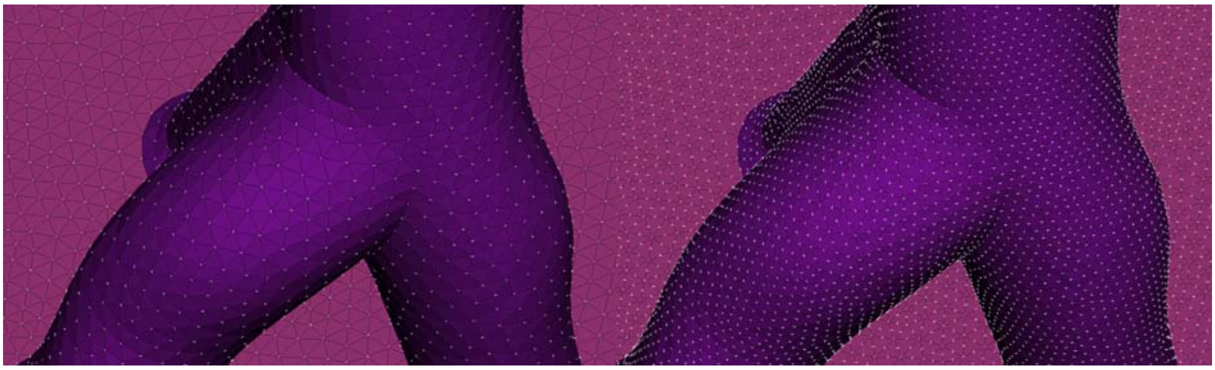
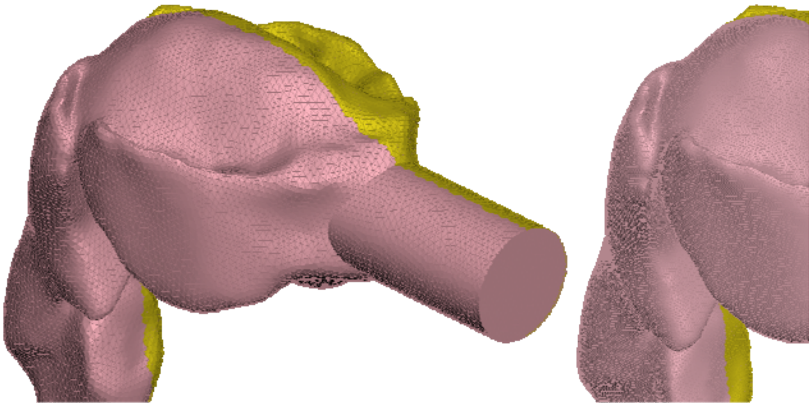


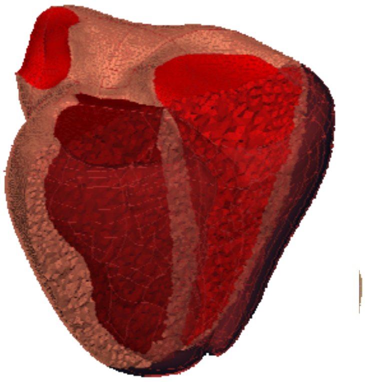
Figure 3 – Surface mesh before (left) and after (right) add a point in the middle of the edges.

Figure 4 – Surface mesh before (left) and after (right) apply the recontructions.

Finally, we are ready to create a volume mesh from this second order surface. After that we have to check there are no negative volume in our mesh and then our mesh it is prepared to be simulated.

Figure 5 – Final meshes, quadratic elements (left) and lineal elements (right).





2.2 HUMAN HEART

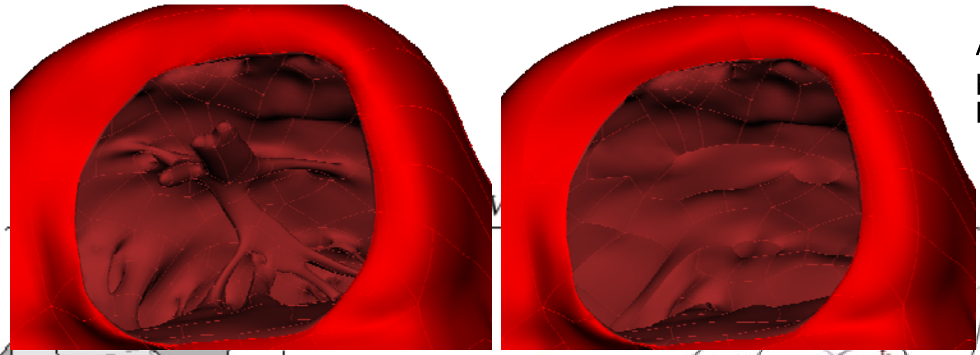
In the case of the human heart, it is really unlikely to find an experiment against which to validate. Indeed, with the application of fluid-structure itnteraction to this model we try to reproduce a physiological deformation of the heart. In this case, the objective is to reproduce the ventricular dynamics, but not to validate the resuslts, as there are not any in-vivo measurements. In the end, what we will look for it is to reproduce a simular behavior of the organ. With this intention, a boundary representation of a heart was provided to us which mesh generation will be discuss in this chapter.

After importing the differents parts of the geometry to ANSA enviroment, we found that the model had intersetions and the different parts did not fit each other. Hence, we decide to change the way we face this problem. Instead of using the whole model, to start from the basic parts and then going adding different elements.

Figure 6 – Ventricles.

The first approximation was to use just the ventricles. It is a big simplification but it is common in this type of simulation some authors even cut them by a plane close to the baseto create a planar outlet. We will not go so far because we want to maintain the geometry as intact as possible. So we generate new surface to define the boundary for our problem using the curves of the model.

After generating the mesh we faced a problem that is currently unsolved. The deformation of the fluid mesh may in some cases invert the elements crashing the simulation. To avoid to finalize the simulation for this problem we decide to eliminate all the trabeculaes that can produce a possible penetration with any part of the ventricle (Figure 7).



At this point, we have a robust

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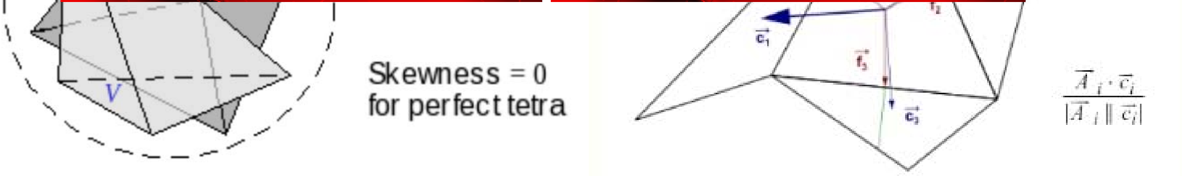


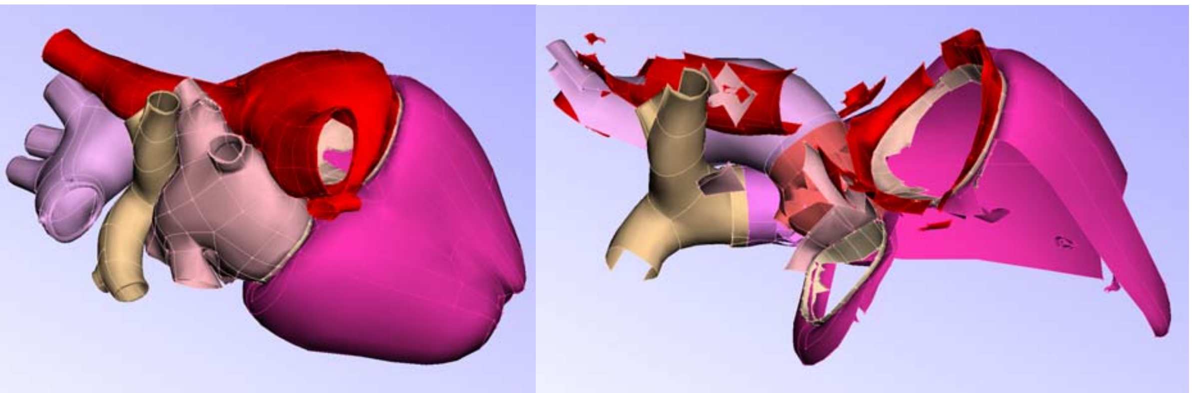
Figure 8 - Definition of quality criteria: skewness (left) and orthogonality (right).

“geometry”, so we decide to explore some quality criteria to observe the influence in the convergence of the results. We decide to focus on the skewness and ortogonality (Figure 8) of the volume elements because elements too distorted can crash the execution due to the invertion of the elements or the divergence of the fluid simulation.

Hence, we decided to run seven simulation under the same conditions with meshes generated with diferents parameters of these quality criterias. The characteristic of the meshes are shown in the figure 8. All the meshes have been generated taking as base the same surface mesh. The calculation was run during 6 hours with 128 CPU’s (96 for the solid and 32 for the fluid) with the objective of simulate 0.15 secs what imply 1,500,000 time steps for the solids and 30 for the fluid. In the next you can see a descriotion of the diferent meshes and the mean value of the iteration per the time step of fluid simulation.

NAME	**OR-0.8**	**OR-0.6**	**OR-0.4**	**OR-0.2**	**SK-0.8**	**SK-0.6**	**SK-0.4**
NODES	134516	143871	150782	158494	158497	153099	143814
BOUNDARIES	57256	57256	57256	57256	57256	57256	57256
ELEMENTS	752715	810757	851132	898897	898987	867600	810417
MAXIMUM SKEWNESS	0,693	0,839	0,963	0,994	0,8	0,6	0,4
MINIMUM ORTHOGONALITY	0,8	0,6	0,4	0,2	0,224	0,440	0,635
MEAN ITERATIONS PER TIME STEP	**28,4**	**30,5**	**Diverged**	**Diverged**	**Diverged**	**32,9**	**30,2**

In view of these results, we have some guideline of which parameters we have to seek when we will generate new meshes and how to avoid the possible problem of contact between solids parts. So, in this moment we decide to move along an aenlarge the geometry. For the last case we incorcoporate: the valves (aortic, pulmonary, tricuspid and mitral), both atriums, the aortic arch and the pulmonary trunk. As we expected, several intertections appear, even thought it seem that the model does not havethis problem (Figure 9).



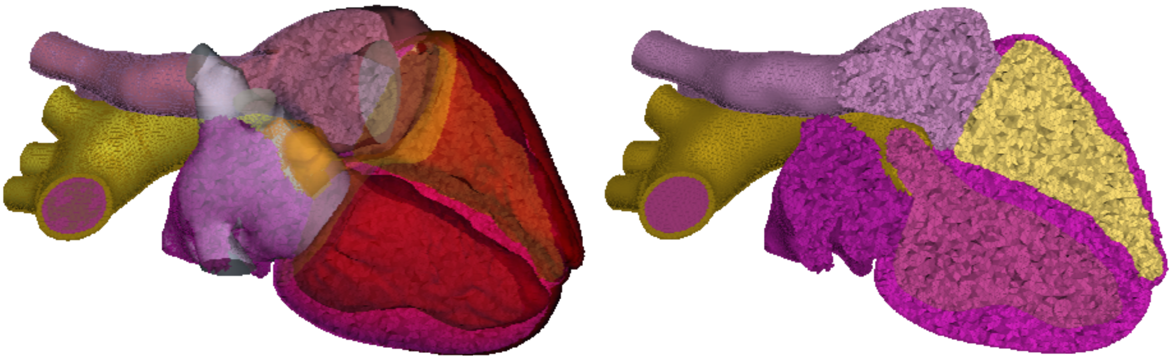


Figure 9 – Ventricles, valves and atriums representation ans their intersections.

Once fixed all these problems we can generate a mesh with the parameters we had determined during the ventricle mesh generation. The result it is shown in the Figure 10.

3. RESULTS

The evaluation of the mesh quality can be done by different criterias. However doing the simualtion is when real performance of the mesh is evaluated. Consequently, we will present some of the results of the meshes we have shown along this work.

3.1 LARGE EDDY SIMULATION

Figure 10 – Volumes mesh of the ventricles, valves and atriums.

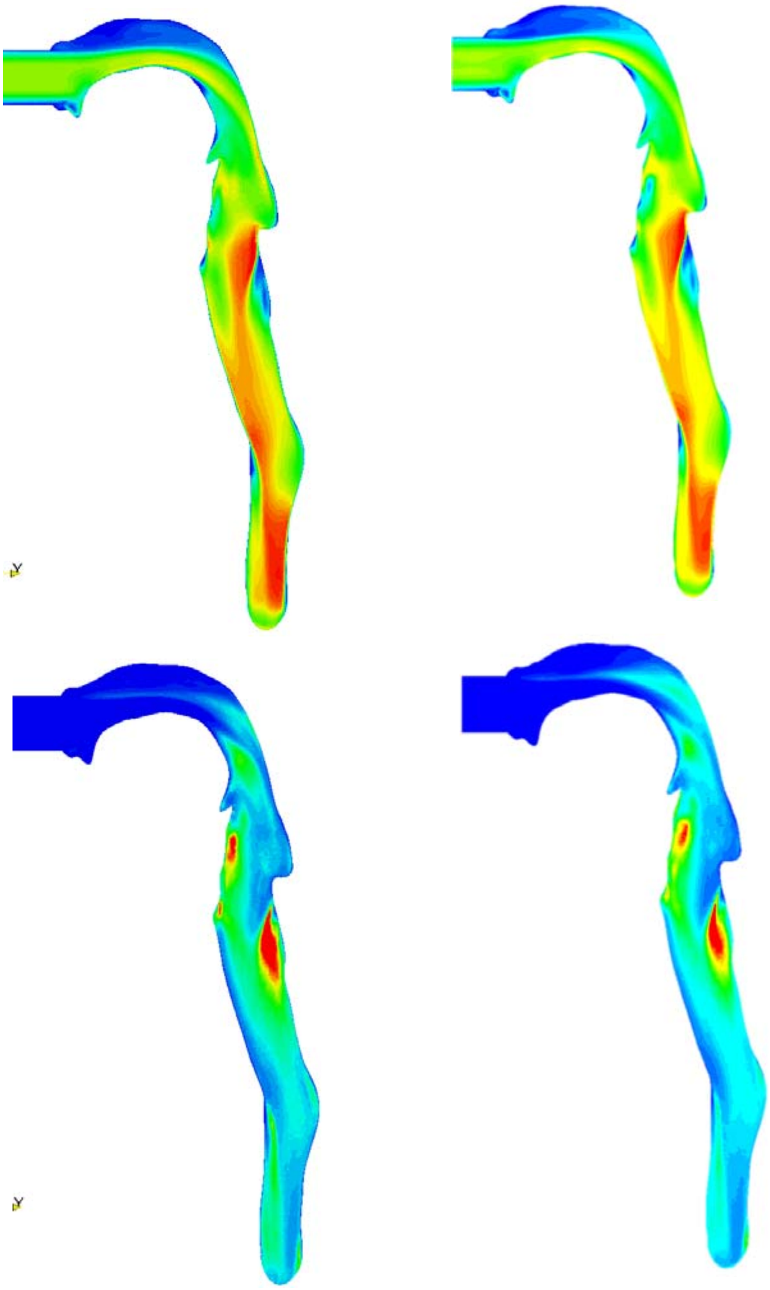


Figure 11 - Mean velocity (up) and turbulent kynetic energy (down) of the respiratory system.

The model of the respiratory was simulated with Wall-Adapting Local Eddy-Viscosity (WALE) model as sub-grid scale (SGS) closure, a Courant–Friedrichs–Lewy (CFL) condition of 0.95 and during $3.5\cdot10^5$ time steps. The goal of this simulation is to have a similar results with a coarse mesh full of tetrahedras (6.5 million elements) and another with boundary layer (7 million elements), to the ones obtained with another finer (50 millions elements), with boundary layer too, simulated with a open source code (OpenFOAM). All the meshes have lineal elements. The mean velocity and turbulent kynetic energy of the Alya simulation are presented below (Figure 11).

As we can see in the Figure 11, the mesh without boundary layer it is overpredicting the flow velocity and in some regions it is not detecting well the zones of recirculation. This is due to that the subgrid it is not well resolved in this case.

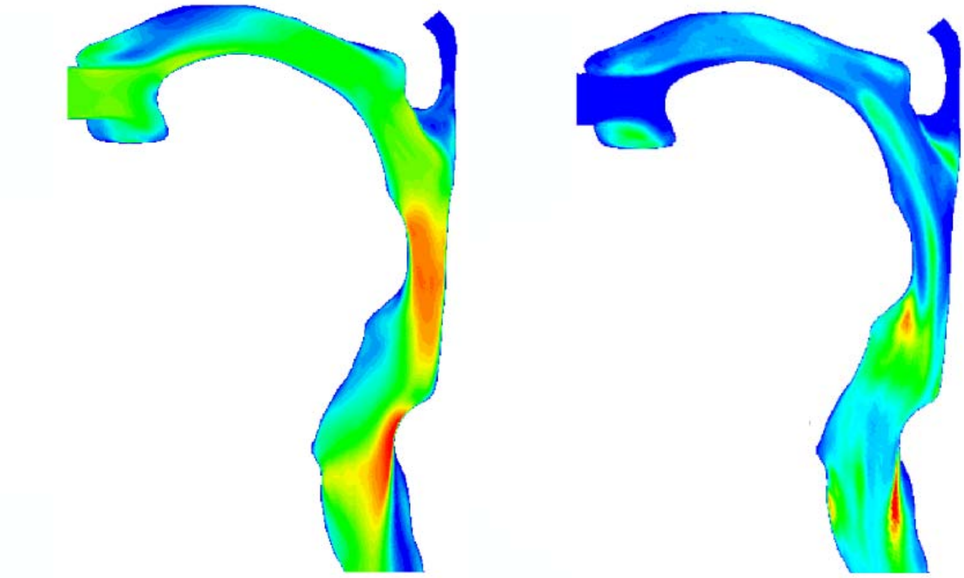
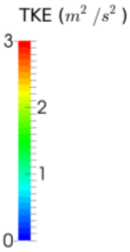


Figure 12 - Mean velocity (left) and turbulent kynetic energy (right) of the mouth-trachea.



Additionality, we present the results of another geometry formed by the mouth and trachea with the same objetives than the respiratory, get similar results with a coarse mesh. In this case, the mesh was generated with quadratic elements and the model used it was the Integral Length-Scale Approximation (ILSA) subfilter scale (SFS) model proposed by Piomelli et al. The complexity of this geometry is comparable to the respiratory system but in this case we only use 950 thousand elements due to the better matched of the model. As before, the mean velocity and turbulence kynetic energy are shown following (Figure 12).

3.2 FLUID STRUCTURE ITERACTION

The FSI simulation of a heart it is more complex than just FSI because we have to model the electrophisiology pulse that produce the deformation of the solid and consequently the fluid dynamics. We go beyond and this pulse is propagated over the deformed domain something that the industry do not use to do. The application of this condition to the ventricles gives as result the following mass flows over the time and the pictures show the evolution of the mean velocity and the propagation of the electric pulse over the ventricles (Figure 13).

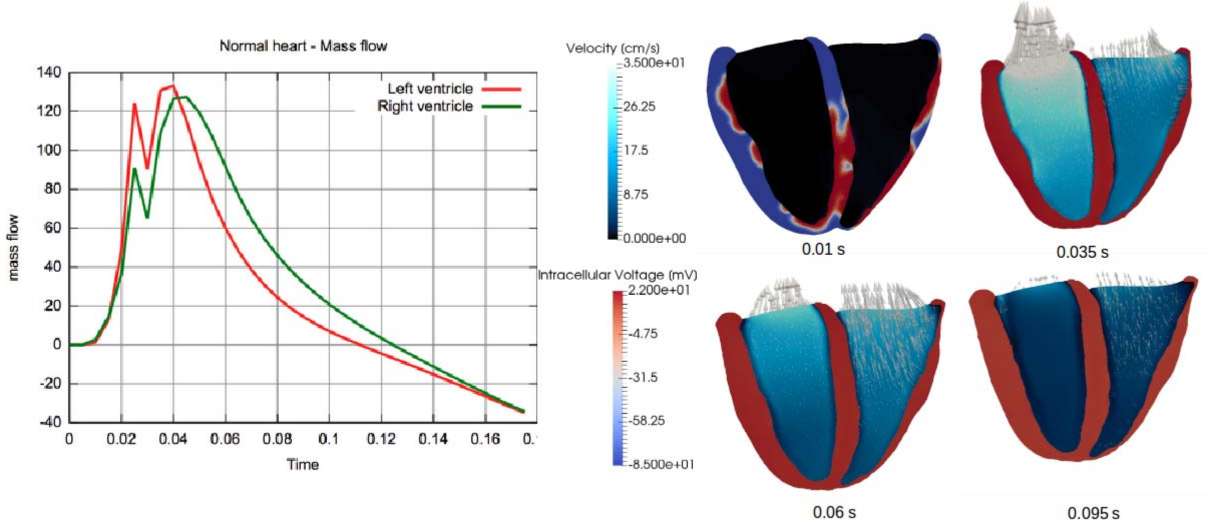


Figure 13 – Mass flow and evolution of the heart over the time

X. CONCLUSIONS

Along this paper we show some guidelines for generating quality meshes for biomechanics taking into account from the source of the geometry to the type of simulation.

In order to choose one or another type of representation (boundary representation, medical image or tesselation) will depend on the goals of our experiment. Thereby if we want to simulate the behavior of an organ, it is possible use any of them (tesselation, boundary representation or medical images). The best option is a boundary representation, but if the objective is to compare with an experiment we most use tesselation or medical images.

When you generate mesh from tesselation you need to take care about the possible gaps that can appear. The generation of good quality mesh with lineal elements is straight forward, the difficulties appear when you try to generate quadratics elements and you want to match the geometry, it is there where you have to take advantage of the ANSA’s tools. Additionaly, during the volume mesh generation start to appear negative volumes that don’t usually appear with lineal elements.

The parameters studied during the mesh generation of the ventricles give us the idea that the more orthogonal is the mesh better is the convergence and, also, it is less probable the divergence of the problem.

However, if you do not resolve a problem you do not really know if the discretization of your model is good enough to represent the reality. Hence to know with certainity if our mesh is reliable, we have to simulate. For example, it exists a big difference between the mesh without boundary layer and with boundary layer of the respiratory system, and the difference of elements is only 0.5 million (7%).

To sum up, we were able to show how parameters influence in the results and the convergence of the problems. Additionally, we prove that with Alya is possible to have similar results with meshes 7 times coarser.