

Combining Mimics and computational fluid dynamics to assist in and evaluate the placement of an intrabronchial stent in a patient with congenital kyfosciosis

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Abstract

Advanced functional imaging techniques using Mimics and flow simulations can increase the insight in lung dynamics and can increase the efficiency of the treatment. The novel character of, and additional information obtained with this new method have been shown in this paper by means of a case study.

The studied patient was a young female suffering from kyfosciosis who experienced a wheezing sound at deep inspiration since she was no longer obliged to wear an orthopedic corset to limit the amount of spinal deformation. The construction of three dimensional models of the spine, the lung lobes and the airway tree at total lung capacity directly drew the researchers attention to quasi-atelectasis of the right lower lobe and the occlusion of the airways going to this lobe. The combination of small bronchial diameters and ventilation that was only present at high flow rates, was found to be responsible for the wheezing sound.

Based on the findings a therapy was suggested that would overcome the underlying reason of wheezing, i.e. the obstruction in the airway passage to the right lower lobe. For this purpose a stent has been designed based on measurements on the reconstructed airway tree.

After insertion of the stent the patient has been re-evaluated after 1, 6 and 7 months. Functional imaging using Mimics and flow simulations have shown that the patient's lung dynamics got better over time after the insertion of the stent.

The new techniques are believed to optimize the patient specific healthcare by increasing the insight in lung dynamics in general. They provide a source of additional information on top of the standard clinical parameters and will allow clinicians to select the adequate treatment in each patient. The authors believe that advanced functional imaging techniques will become standard evaluation tools in pulmonology.

1. Patient Description and Study Goals

This paper presents the results of a case study performed at the University Hospital of Antwerp. The patient was a 16 year old Caucasian girl (weight: 52 kg, height: 184 cm) suffering from congenital kyfosciosis or deformation of the spinal chord. Kyfosciosis consists of a combination between scoliosis (sideways deformation) and kyfosis (forward/backward deformation). To minimize the deformation of the spinal chord children often wear an orthopedic corset until they are fully grown. The patient did wear an orthopedic corset until the age of 16. The deformation of the spinal chord at this point in time can be seen in Figure 1. From this figure a serious deformation of the spine towards the right could be observed.

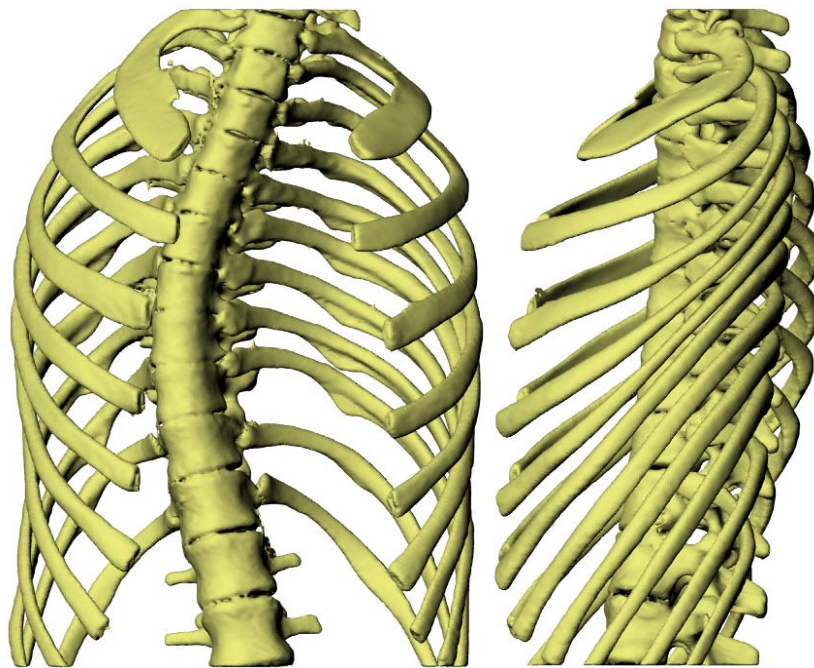


Figure 1 Visualization of kyfosciosis patient at the age of 16

The patient was consulted at the department of pulmonology because of the presence of wheezing during deep inspiration. The sound had only been present since the patient did not wear the orthopedic corset anymore. Classical lung function tests showed a severe restrictive lung function with a total lung capacity (TLC) of 3.37 liters or 57 % percent of the predicted value in Caucasian females of that age and length. Further demographic and lung function data of the patient can be found in Appendix A.

The **goal** of the study was to use advanced functional imaging techniques as a diagnostic tool to *determine the causes of the patient's complaints*. The functional imaging method consisted of the combination between Mimics and numerical flow simulations. Once the pathology was understood, a *suggestion for therapy* could be done. A last study goal was the *evaluation of the proposed therapy* using the same advanced functional imaging techniques.

2. Pathology Evaluation

To get a better understanding of the origin of wheezing, a high resolution low dose CT scan was taken from the patient. To capture the phenomena that cause the wheezing the scan was taken at the lung level at which the wheezing occurs, i.e. total lung capacity (TLC). An in-house developed monitoring device was used to make sure that the CT scan was taken at the desired lung level.

From the resulting CT data set a three dimensional (3D) reconstruction of the spine (see Figure 1), the lung lobes and the airway tree has been made using the Mimics software package (Materialise, Belgium). The reconstruction of the lungs was performed semi-automatically using a sequence of mask and contour operators. To accurately reconstruct the different lobes in each lung, a certain number of points on the fissures (i.e. the separation lines between the lobes) were highlighted. These points were used to construct surfaces (Rhinoceros Nurbs 3D, McNeel, Seattle, USA) which could be imported again in Mimics (.stl format). Boolean operators resulted in the wanted lobular volumes. For the airway tree reconstruction also a semi-automated procedure of mask operators was applied. This allowed for a reconstruction of the airway tree up to the level of the 5th-7th bifurcation.

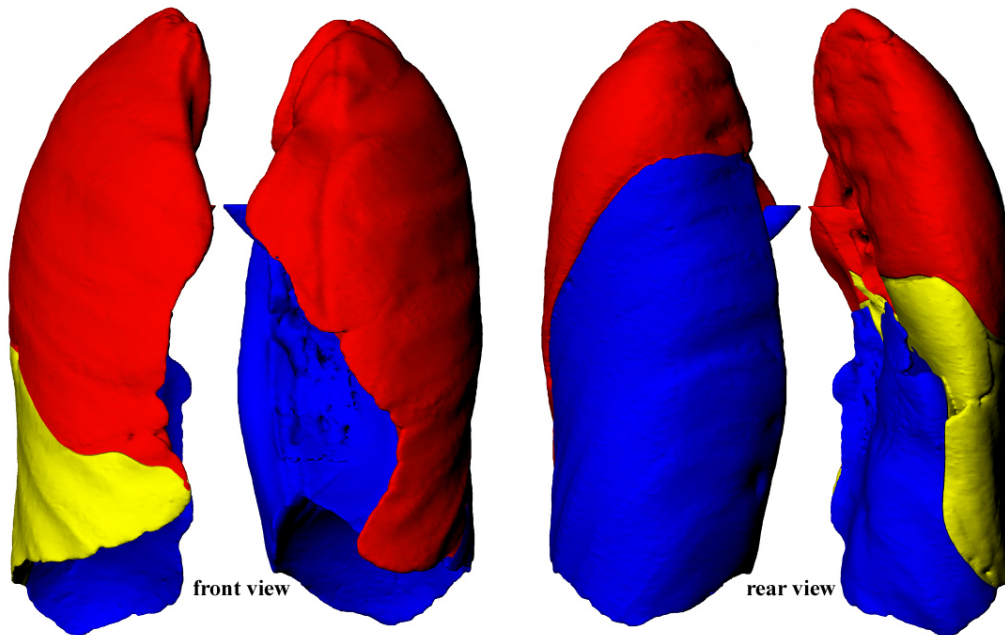


Figure 2 Lobular distribution at TLC in patient before treatment

The reconstructed lobes can be found in Figure 2. In this figure the lower lobes (LL) were colored in blue, the middle lobe (ML) in yellow on the upper lobes (UL) in red. It can be seen from this figure that the lungs were indeed affected by the deformation of the spine towards the right side (as could be seen in Figure 1). The deviations from the normal lung structured could be observed in the slightly larger upper and middle lobes

and a drastically smaller right lower lobe (LLR, almost a complete atelectasis¹). A visualization of the lobular distribution in a healthy person compared to the patient can be found in Appendix B.

The reconstructed airway tree can be seen in Figure 3. In this figure a serious malformation of the airway tree in the right lung could be observed. At the level of the truncus intermedius and the lower lobe bronchus (indicated with the red dotted circle in Figure 3) the airways showed a quasi-complete occlusion due to the curvature of the spine. No deformations were observed in other parts of the airway tree.

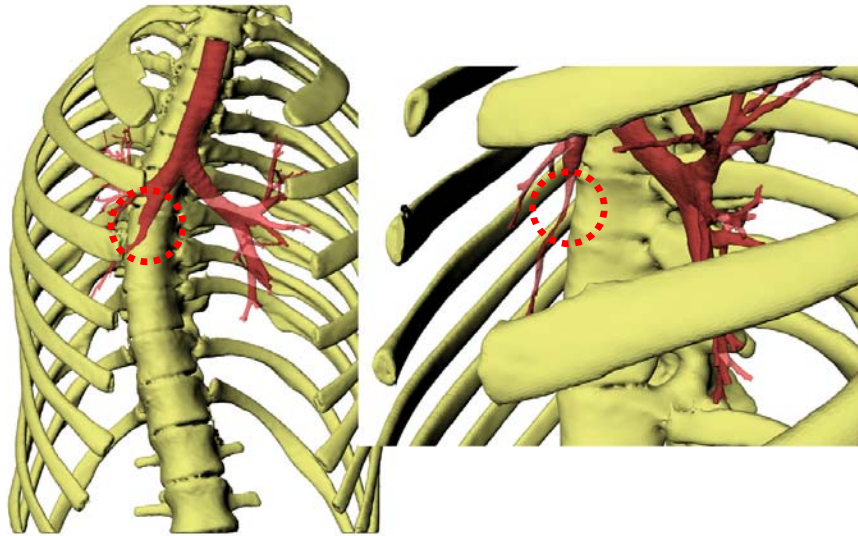


Figure 3 Airway tree for patient at TLC before treatment

The extremely small lower right lobe in combination with the (quasi) occluded airways leading to this lobe was believed to be part of the explanation of the wheezing sound. During the period that the patient was wearing an orthopedic corset to minimize the spinal deformations, the extrabronchial pressures exerted on the truncus intermedius and the right lower lobe bronchus, by both the corset on one side and the spinal chord on the other side, were so large to cause a total collapse of the airways leading to the right lower lobe, thus preventing any air from reaching this lobe.

Once fully grown and no longer obliged to wear the orthopedic corset, the pressure from the corset on the patient's airways leading to the right lower lobe disappeared. This allowed for the right lower lobe to be ventilated, but due to the fact that the pressure on the airways from the spine this only happened at high lung volumes when the truncus intermedius opened marginally. The combination of a small bronchial diameter at the level of the truncus intermedius and high mass flow rates at larger lung volumes caused a flow with high velocity in this bronchus. This flow was believed to cause the wheezing sound.

¹ Atelectasis: Atelectasis is the collapse of part or all of a lung by blockage of the air passages (bronchus or bronchioles), or by very shallow breathing.

3. Therapy Suggestion

Therapy had to be such that the ventilation of the right lower lobe improved. After treatment air had to reach this lobe during the complete breathing cycle and not only at high lung volumes through narrow bronchi, i.e. the phenomenon responsible for the wheezing sound. To achieve this, an intervention had to be designed that caused both an increase in airway diameter and a constant ventilation of the right lower lobe.

An intrabronchial stent, positioned in the highly pressurized truncus intermedius, was believed to be suited to overcome these problems (Al-Kattan et al., 1997). As could be seen from the coronal view in Figure 3, the diameter of the truncus intermedius was flatted in sagittal direction due to the high extrabronchial pressures. The sagittal view in this Figure 3 showed that the diameter in coronal direction remained unaffected by the extrabronchial pressure. In Figure 4 a detailed sagittal view of the truncus intermedius with its expected length and diameter is given.

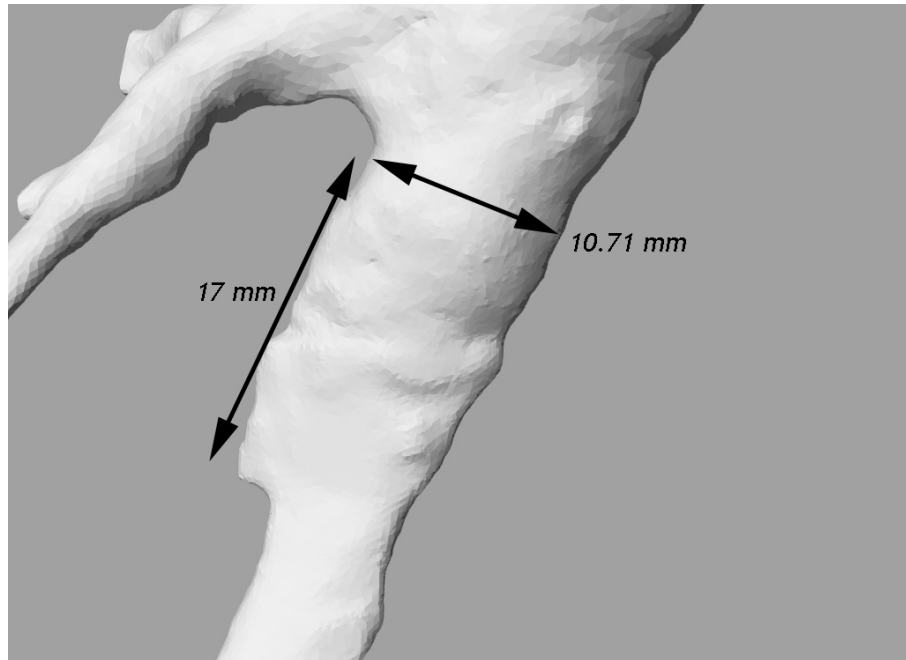


Figure 4 Dimension of the highly pressurized truncus intermedius

These results provided the dimensions of the intrabronchial stent, i.e. a diameter of 11 mm and a length of 17 mm. This stent was to be inserted in the truncus intermedius during a bronchoscopy.

4. Evaluation of Therapeutical Outcome

The outcome of the therapy was evaluated using data from different sources. First of all clinical data, i.e. lung function tests, were collected at 1 month, 6 months and 7 months after the placement of the stent. Furthermore the patient underwent a second high resolution low dose CT scan one month after the placement. This scan was treated in exactly the same manner as described in section 2 in order to evaluate lobular changes. Also flow simulations were performed to investigate the flow and resistance distribution in the airway tree. Finally the patient received a third CT scan (low dose, low resolution) 6 months after the insertion of the stent. This CT scan was accurate enough to study the lobular structures, however due to the limited resolution no airway tree has been extracted. (Lee et al., 2005)

The first therapeutical outcome, before going into detail on the lung mechanics, was the disappearance of the wheezing sound once the stent was in position. This strengthened the believe that indeed small diameter and high velocities in the truncus intermedius caused this phenomena. From Figure 5 it can be seen that the stent was indeed in the planned position and that the diameter of the truncus intermedius was indeed positively influenced by the stent.

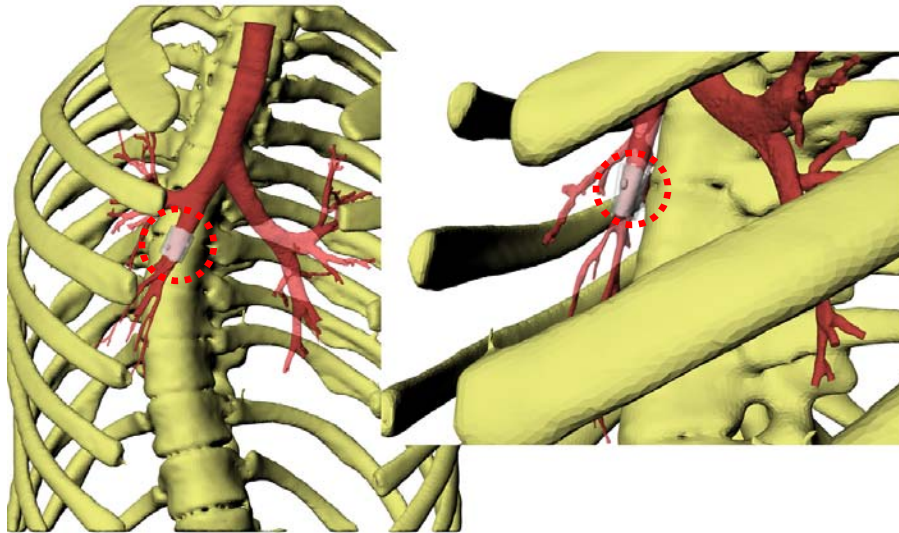


Figure 5 Airway tree for patient at TLC 1 month after treatment

Regarding the clinical outcome of the lung function tests it became clear that the insertion of the intrabronchial stent had a significant influence on the restrictive lung function problem as observed before treatment. The total lung capacity increased in a period of 7 months from 57 % to 68 % of the predicted value. This can be seen in Figure 6. From this figure one can see that the growth in lung capacity happened quasi-linear over time. (Vergnon et al., 1995)

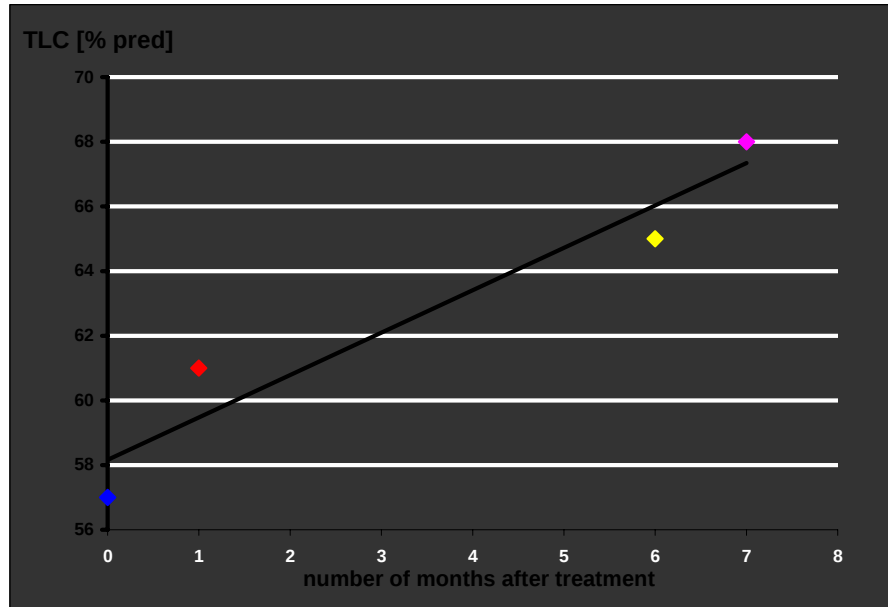


Figure 6 Total Lung Capacity over time in patient after treatment

Looking on a lobular scale, using the CT scans that were taken before, 1 month and 6 months after the treatment, allowed for a better understand of mass flow repartition in the lungs. Figure 7 shows how the lobular volume distribution changed as the total lung capacity increased after the insertion of the intrabronchial stent. It can be seen from this figure that the right lower lobe (LLR), which was drastically smaller as expected (Figure 14 in Appendix B), showed the largest change.

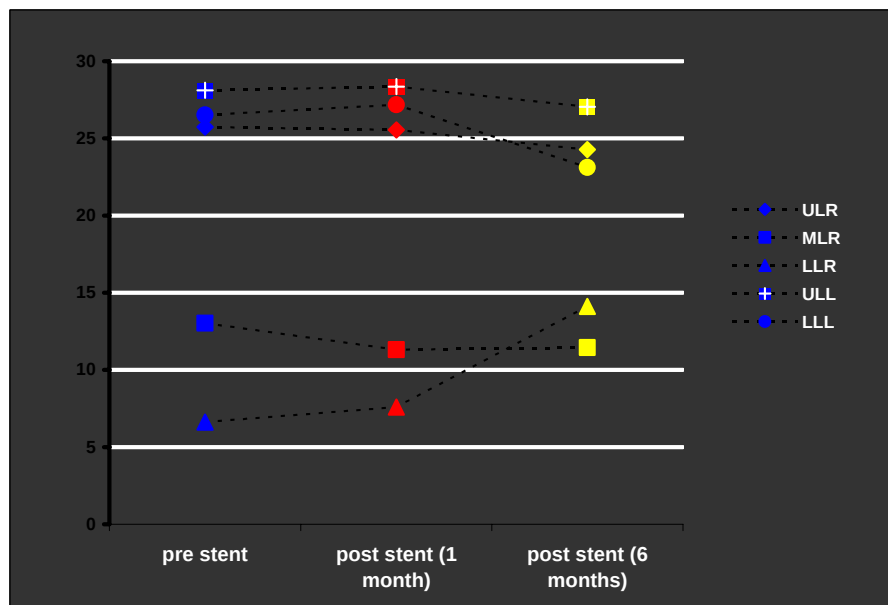


Figure 7 Lobular distribution change in patient over time after treatment

From Figure 8 (b) it can be seen that in the first month mainly the right middle lobe (MLR) and right lower lobe (LLR) showed a volume repartition. Afterwards the volume

repartition happened more homogeneously between the upper and lower lobes (Figure 8 (c)).

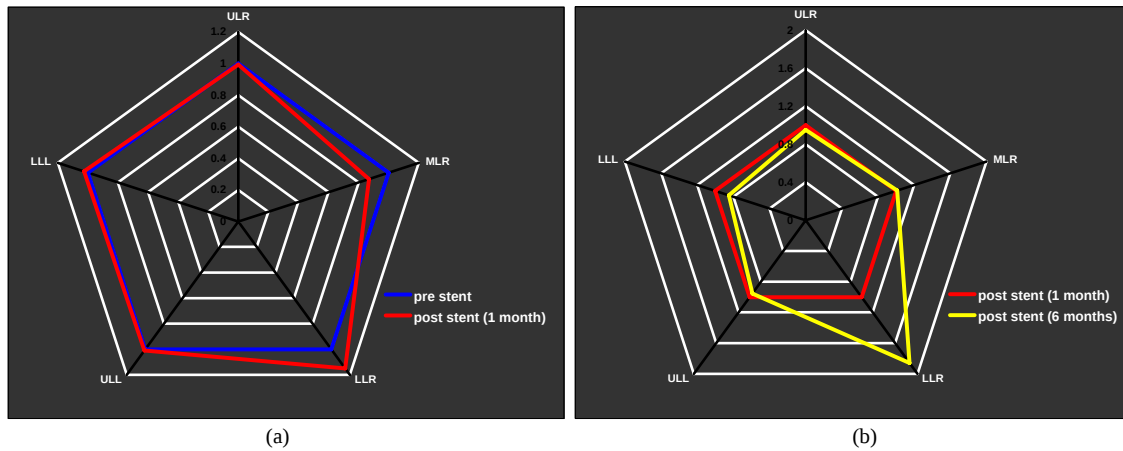


Figure 8 Lobular distribution change in patient over time after treatment

Considering only the right lower lobe (LLR) it became clear from Figure 7 and Figure 8 that this lobe did get the largest amount of redistributed air in the lungs. Starting of, before the treatment, at only 6.5 % of the total air inside the lung, this lobe increased its relative volume to 14 % of the total air 6 months after therapy. From Figure 9 it can be seen that this increase in relative volumes happened linear over time and the relative volume was expected to reach the level of a healthy person 18 months after the insertion of the stent. However it must be taken into account that the deformation of the spinal chord remains and that therefore the patient might never completely reach the level of a normal person.

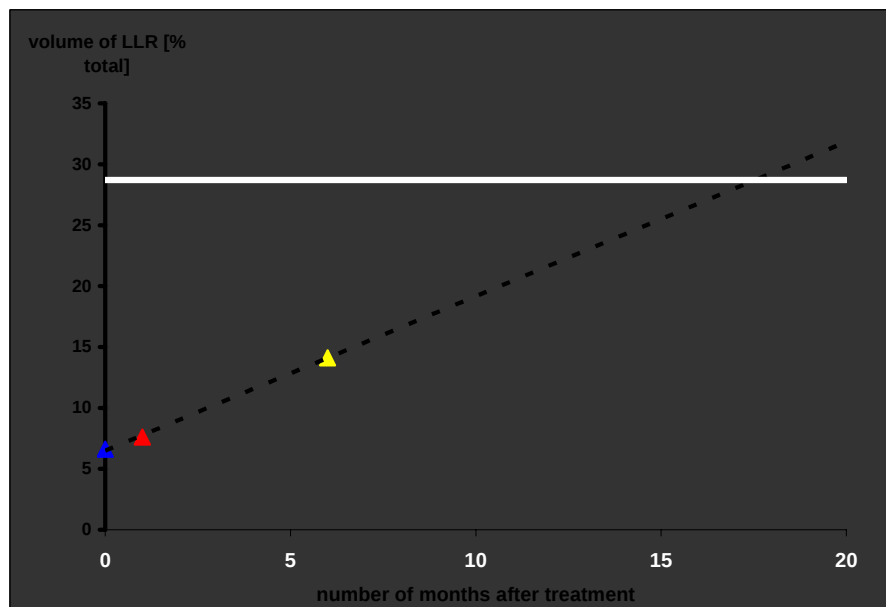


Figure 9 Relative volume of the right lower lobe in patient over time after treatment with indication of expected relative volume in healthy persons

Also flow simulations have been performed to investigate the influence of therapy on flow and resistance distribution towards the lobes. The flow simulations were performed on the reconstructed bronchial trees using computational fluid dynamics (CFD) techniques. These techniques solve the Navier Stokes equations in a well defined domain. As boundary conditions for the CFD computations the airway wall was set as impermeable with a no slip condition. At the trachea a pressure inlet surface was used with a constant pressure, $p = 0$ Pa. The outlet surfaces in the bronchi were defined as pressure outlets with a constant under-pressure, $p = -1000$ Pa. The Reynolds-averaged Navier Stokes (RANS) equations were solved with the pressure-based, implicit, steady, laminar, incompressible flow solver in the Fluent software package (Ansys Inc, Lebanon, USA) until convergence of the mass flow rate throughout the model was reached.

From the resulting data it was possible to compute mass flow (Mflow) and resistance (RAW) distributions. From Figure 10 it can be seen that the total resistance of the reconstructed model did decrease after the insertion of the stent. Consequently, because of the equal under-pressure that was set as a boundary condition on the outlet surfaces, the mass flow rate did increase.

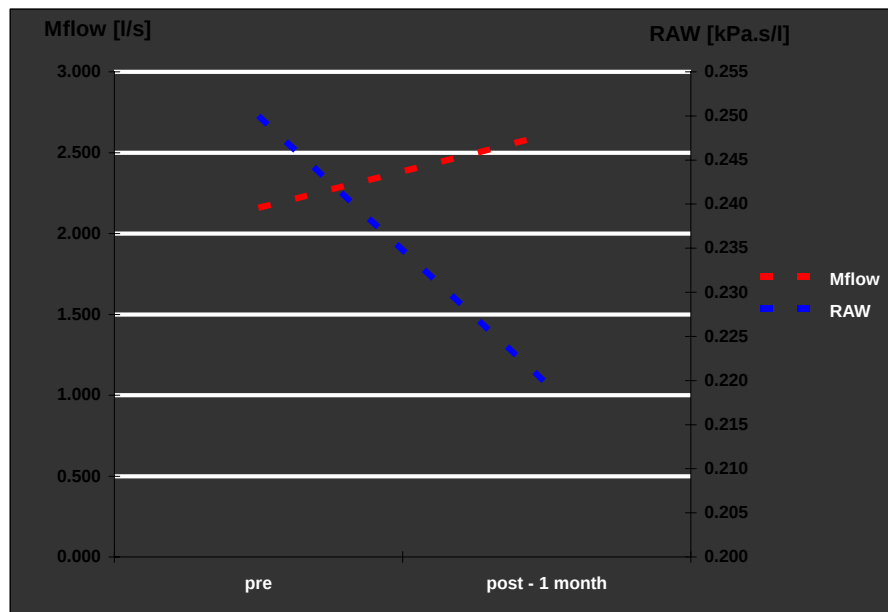


Figure 10 Mass flow and resistance changes for patient 1 month after treatment

Because the therapy was aiming for a better ventilation of the right lung it was worthwhile to investigate the mass flow and resistance distributions towards the right and left lung. From Figure 11 it can be seen that the resistance in the right lobe was more than twice as high as the resistance in the left lobe before treatment. One month after the insertion of the stent the resistance of both lungs had an almost equal influence on the total resistance. As a consequence of this a similar behavior could be observed for the mass flow distribution. Because of the high pre-treatment resistance in the right lung this lung was badly ventilated (only 30 percent of the inspired air went to the right lung). After treatment the mass flow rate balanced out and both lungs were ventilated in the same amount.

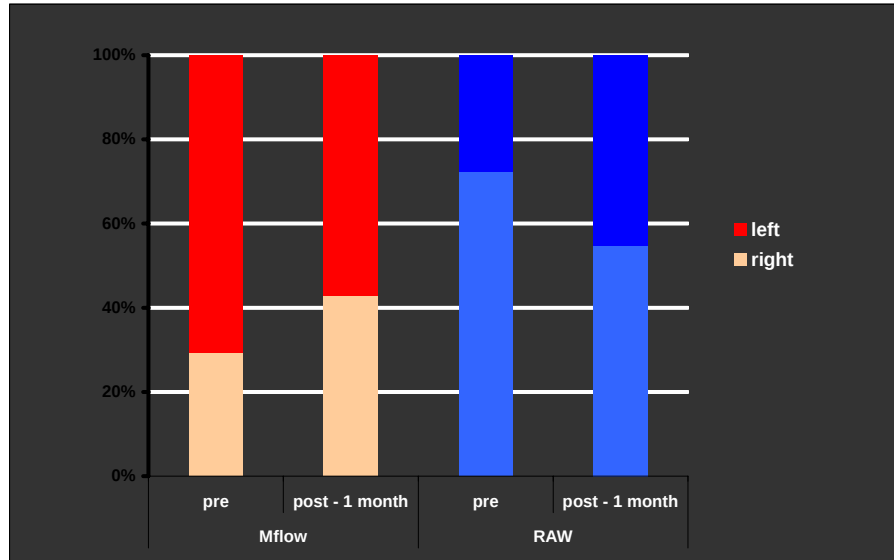


Figure 11 Right/left distribution of mass flow and resistance in patient before and after treatment

5. Conclusion

In this paper it has been shown that the use of advanced functional imaging techniques can be used for patient specific pulmonary problems. The three goals that were set before the start of the study have all been met.

Pathology Evaluation

It has been shown that advanced functional imaging techniques could locate the exact origin of the wheezing sound in the patient. The cause was situated in the truncus intermedius. The techniques did not only pick up the problem, they also provided a lot of additional information on the patient's lung function. A partial atelectasis of the right lower lobe was observed due to the presence of occlusions in the bronchi leading to this lobe. These occlusions were caused by the high extrabronchial pressure resulting from the patient's spinal deformation.

Therapy Suggestion

The reconstructed 3D models of the airway and the improved insight in the patient specific respiratory dynamics assisted in determining an adequate therapy to overcome the wheezing sounds and to increase the ventilation of the right lower lobe. The suggested therapy was the placement of a stent in the truncus intermedius. Accurate measurement of the reconstructed models provided the clinician with the exact dimension of the intrabronchial stent.

Evaluation of Therapeutical Outcome

Using the same techniques that were shown to accurately evaluate a patient specific pathology as well as provide a patient specific therapy, it has been shown in this paper that the outcome of a therapy can be evaluated using advance functional imaging techniques. The techniques allowed for a comparison of the pre and post treatment lung dynamics. It has also been shown that predictions towards future changes in lung function caused by the insertion of the intrabronchial stent could be made. However it must be taken into account that the deformation of the spinal chord remains and that therefore the patient might never completely reach the level of a normal person.

Overall it can be said that innovative advanced functional imaging techniques using Mimics and flow simulations can improve the level of healthcare in the field of pulmonology through patient specific analyses. This has been demonstrated by means of an example but the same techniques can be used on different patient with different pathologies. The technique is believed to allow pulmonologists to choose for the right treatment method for each individual patient, thus increasing their quality of life and decreasing the patient's contribution to the cost of healthcare.

The versatility of the technique and the positive outcomes when used in a clinical setting strengthens the believe that functional imaging using Mimics and CFD can become a standard tool in pulmonology worldwide.

6. References

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Lee, K. S., Lunn, W., Feller-Kopman, D., Ernst, A., Hatabu, H., Boiselle, P. M., (2005). Multislice CT evaluation of airway stents. *J Thorac.Imaging* 20, 81-88.

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Appendix A

Table 1 Demographic and lung function data for the patient

Patient ID				
Age [years]	16			
Sex	F			
Weight [kg]	52			
Length [cm]	183			
	<i>Pre</i>	<i>Post - 1 month</i>	<i>Post - 6 months</i>	<i>Post - 7 months</i>
Spirometry				
FEV1 [l]	1.89	1.99	2.24	2.11
FEV1[% pred]	45	49	55	52
FEV1/VC [-]	86	89	89	86
Lung Volumes				
TLC [l]	3.37	3.54	3.70	3.95
TLC [% pred]	57	61	65	68
FRC [l]	1.84	1.81	1.89	2.04
FRC [% pred]	63	64	66	72
RV [l]	1.18	1.30	1.22	1.49
RV [% pred]	91	103	97	118

Appendix B

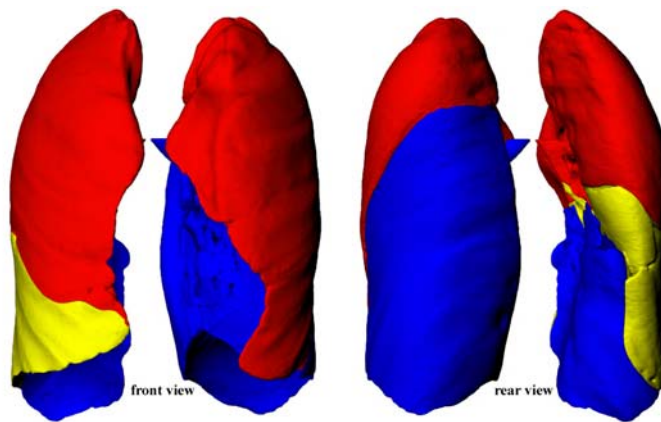


Figure 12 Lobular distribution at TLC in patient before treatment

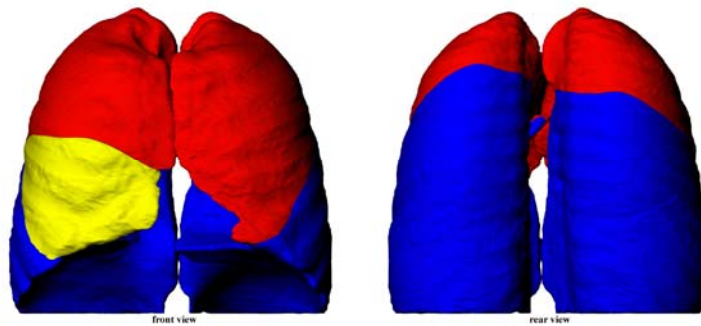


Figure 13 Lobular distribution at TLC in healthy person

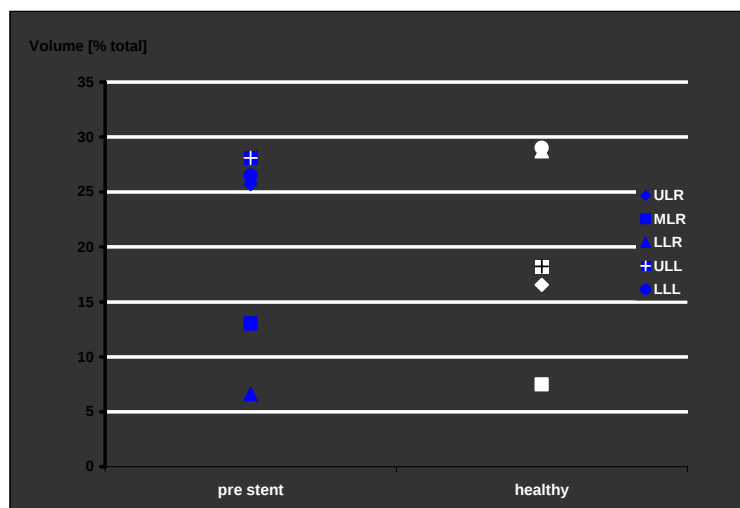


Figure 14 Lobular distribution: patient vs healthy