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Abstract

Nasal breathing difficulties (NBD) are a widespread medical condition, yet decisions pertaining to the surgical treatment of chronic NBD still imply a significant degree of subjective judgement from the surgeon.

The current standard objective exams for nasal flow, e.g. rhinomanometry and acoustic rhinomanometry, do not suffice to reliably direct the surgeon on the extent of any necessary surgery. In the last two decades several groups have therefore considered the numerical simulation of nasal airflow. Currently these analyses take many hours of labor from the operator, require a huge amount of computer time and the use of expensive commercial software. Most often, their results are unsufficiently validated so that virtual surgery, which is the eventual application, still is absent from clinical practice. Very recently, however, attempts to consider the finest details of the flow are beginning to appear, for example unsteady turbulent simulations validated through laboratory measurements through Particle Image Velocimetry. In this paper we first discuss recent developments in how Computational Fluid Dynamics (CFD) is helping surgeons improve their understanding of nasal physiology and the effect of surgical modifications on the airflow in the nasal cavity. In a second part, the procedural and modelling challenges that still prevent CFD from being routinely used in the clinical practice are surveyed and critically discussed.

Keywords: Computational Fluid Dynamics, nasal cavity, 3d model, airflow, surgical planning

Introduction

Nasal Breathing Difficulties (NBD) represent one of the most common medical conditions, afflicting tens of million people and accounting for over $5.8 billions in healthcare costs annually in the United States alone [1]. Their surgical treatment pertains to the daily practice of ENT surgeons, and carries heavy social costs.

The traditional surgery for the treatment of chronic NBD consists in a selective approach to the septum and inferior turbinates. Sometimes such surgery is combined with operations on the nasal pyramid that may result in changes in the region of the nasal valve. Nowadays Functional Endoscopic Sinus Surgery (FESS) has taken the place of traditional surgery and is becoming the gold standard for rhinosinusal chronic NBD treatment. It may involve, depending on the patients anatomy, inferior and/or middle turbinoplasty, opening of the paranasal sinuses, ethmoidectomy and septoplasty. These procedures re-establish an adequate nasal aerial flow, thanks to the enlargement of nasal and meatal sections, while also increasing sinus ventilation and improving their draining [2]. However, the nasal valve, which is by far the fundamental area of nasal resistance and is of paramount importance in general in conditioning nasal breathing, is poorly controlled by FESS. Nasal surgery is therefore a field where surgeons need objective indicators to support them in choosing the surgical technique suitable to every particular patient, in relation to his/her specific anatomical and functional features.

Currently rhinomanometry is the only exam that, with a relative accuracy, can describe the nasal aerial patency, by measuring the functional relation between pressure drop and flow rate [3]. However, rhinomanometry provides us with a global assessment only, and does not consider local details of the flow (e.g. in the region of the inferior meatus), that are often extremely significant from a clinical standpoint. The alternate non-invasive test available, i.e. acoustic rhinometry [4], surely produces a more detailed evaluation of the geometry of nasal cavities. However, it does not evaluate the flow field but its geometric boundary only. Furthermore it may only be reliable and repeatable concerning combined (mean) values, not for strictly unilateral values [5] and when performed by the same examiner [6].

The state of the art is thus that we are presently unable to assess the relevance of every single anatomic anomaly and its surgical modification on the overall nasal flow quality and nasal obstruction [7]. Patient history and clinical examination are the starting point, but both are subjective to some degree, and must be critically considered in view of a background of high frequency of septal deviation and other anatomical alterations in the population, joint with a lack of significant statistical correlation between function and status. Furthermore, each surgical procedure is typically carried out according to the surgeon's own experience. We are thus as a consequence unable to predict the effect of any single surgical manoeuvre on the overall nasal flow in an objective way. All the more so, it is currently impossible to foresee the effect of a given surgery-induced modification of the inner-nose geometry upon the local airflow quality, thus affecting for example humidification, possible crusting, bleeding, etc. As an example we consider the most frequent operation performed to improve nasal airflow: inferior turbinate reduction. In the literature there is no agreement upon the correct surgical indications, or the predictable results, or which is, among the many proposed techniques, the most effective. The low- level evidence base for performing turbinate surgery is partly due to the lack of appropriate objective measures to assess the surgical outcome [2].

Offline with respect to the daily clinical practice, the detailed study of nasal airflow has been undertaken in the past by using cadaver noses, or physical models reconstructed from CT and MRI images [8]. However, such models are often impractical or inaccurate [9]. More recently, the advent of modern computational fluid dynamics (CFD) and advanced computer technology, have made the Navier–Stokes partial differential equations numerically solvable. These equations govern the dynamics of a fluid flowing within ducts of arbitrarily complex geometry. CFD thus lends itself to become an useful tool for studying the complex fluid flow phenomena occurring in the upper respiratory airways. Early CFD attempts to address the trans-nasal aerodynamics, using various CT-generated three-dimensional nasal models [10] were based on low-fidelity flow models, and did not go beyond a qualitative description of the salient features of the flow. Since then the quality of the numerical prediction has significantly improved, until, in the very last years, CFD has also been proposed as a viable tool to support patient-specific pre-surgical planning, to eventually succeed at what may be called virtual surgery. See table 1 for an overview of recent CFD development.

In this paper we aim at briefly surveying the most important steps that led CFD to become an important research tool. We will then list and discuss a number of specific problems that are not yet widely recognized but must be faced if CFD needs to advance to a state where it can be truly useful for addressing patient-specific problems.

1 Critical analysis of the steps required to carry out a nasal CFD study

Given the state of the art, as shortly described in the previous section, we now attempt to put into focus the most critical logical steps that, according to our judgement and experience, still need improvements for CFD to play a significant role in the daily clinical and surgical treatment of NBD.

1.1 Reconstructing the geometry

This is obviously the first step of the analysis, and begins with the acquisition of a CT scan (or, less often, MR data). A first crucial aspect concerns the quality of these raw data, and in particular their spatial resolution in the three dimensions. Depending on the slice thickness at which the images are acquired and then reconstructed, results with varying degrees of accuracy are obtained when reconstructing the surfaces of interest. This aspect is not particularly emphasized in the literature, possibly also because the spatial resolution of the CT scans is continuously improving, and this issue can be expected to become less and less important in the future. Nowadays a good spatial resolution can be estimated to be at least 0.3-0.4mm or better in each spatial direction, as for example in Zachov et al [21]. Worst resolutions, of the order of 1mm, as those typically employed in clinical use at least in the axial direction, do not apparently bring about critical consequences in a study limited to the nasal cavities alone. However, better resolutions become essential if one is interested in all the rhinosinusal cavities.

The images acquired through CT scans are raw grayscale images where the various levels of gray correspond to different radiodensities of the tissues. It is crucial to set up a proper filtering procedure to come up with a model that is as coherent as possible with the real geometry. The surface of the nasal cavity is reconstructed in a semi-automated manner by software, selecting first a suitable level of gray by which the whole CT volume is high-pass-filtered. In this way the volume is divided in two portions (within and outside of the airways), and the surface separating them defines the nasal cavity. This step obviously involves a critical choice, i.e. the level of gray implicitly defining the boundary surface. A judicious choice requires the experience and skills of an ENT surgeon, since results may vary considerably for slightly different values of the grey level. This issue plays a key role in a step of the entire procedure which may take a long time to be carried out correctly. In the past, more than one paper already emphasized this problem, in particular Croce et al [15]. However, in this case too, no literature study is available that specifically addresses it by proposing a strategy to minimize the impact of the choice of the gray level, or at least by describing a sensitivity study.

Finally, we note that several authors [18, 22] apply smoothing filters to the reconstructed geometry. Strictly speaking, such a filtering stage is not required. However, a more regular boundary improves the quality of the volume mesh, and the computational efficiency may benefit significantly from this additional step. The quantification of the mismatch between the reconstructed geometry and the true geometry, however, still remains to be determined.

1.2 Setting up the simulation

This second step concerns the set-up of the numerical simulation, as well as the required modelling choices and the generation of the computational volume starting from the boundary surface.

The first issue to be discussed is the choice between considering a laminar or a turbulent flow. Indeed, this is the key modelling choice. CFD studies usually solve numerically some simplified version of the Navier-Stokes (NS) partial differential equations (for example the so-called Reynolds-averaged Navier-Stokes equations (RANS), where a temporal averaging procedure is applied to the pristine equations). If turbulence has to be retained, a so-called turbulence model needs to be included, to re-introduce the effect of turbulence that disappears owing to the time average. The main modelling choice, then, is deciding whether the flow model will or will not account for turbulence, and, if yes, pick up one particular turbulence model from the many available. This choice is not unrelated to the amount of computational resources available, as well as to the degree of approximation one is aiming at. Unfortunately, there is no clear and general answer available. The conventional strategy is that of considering a laminar flow when the flow rate is less than 200 ml/s (see for example the review by Leong et al [2] or Wexler et al [14]). To put this in perspective, consider that the basal flow rate is around 100 ml/s. Though reasonable, this is a strong and often dangerous approximation. First, one must bear in mind the difference between a turbulent flow and a (possibly laminar) flow with separation, presence of recirculating regions and vortices. Moreover, the wide anatomical variations make such a simple rule often too simplistic. Considering the flow as turbulent, however, brings about considerable additional complications, beginning from the choice of the best turbulence model [21- 23]. There are many such models available, and none of them is either good or always better than the others, so that the choice of the best model for the problem at hand is a truly critical step. Moreover, every turbulence model contains free constants, which should be tuned to achieve better results on a particular problem. The available literature reports little critical evaluation of the need to consider the flow as turbulent, almost no discussion of the criterion by which a particular turbulence model is chosen, and no example at all of tuning the constants in order to improve accuracy. A further modelling choice which, at odds with the previous ones, is already quite discussed in the literature is the distinction between steady and unsteady flow, as highlighted for example by Elad et al [17] or Zachov et al [21]. The unsteady, cyclic process of breathing can of course be approximated for simplicity sake as a steady process, by choosing a representative time instant along the cycle. The main features of the flow field can be appreciated from a CFD study under the steady flow hypothesis, and such an approach is often enough for a good preliminary analysis. The unsteady case of course implies a much higher computational cost, roughly speaking up to two orders of magnitude. Moreover, the temporal variation of the physical variable driving the breathing process, say the pressure difference between the outer ambient and rhinopharynx, must be assigned. This temporal variation can be assumed to be sinusoidal, as done for example by Elad et al, Naftali et al, Ishikawa et al [16-18]. Zachov et al [21] employed a much more realistic approach by using experimental data acquired through rhinomanometry. It is interesting to note that the choice of the physical quantity driving the flow is not unique: one can modulate in time the pressure gradient, or the flow rate. It is unclear whether these two choices will lead to significantly different results. Driving the flow with a pressure difference is perhaps more physically sound, although many papers describe simulations where the (constant, or time-modulated) flow rate is chosen to drive the flow. To close this section, it is useful to recall the remaining approximations that are involved in the CFD simulation of the airflow in the nasal cavity. The most important consists in neglecting the mucosal lining of the cavity. Although its presence can be indirectly simulated by introducing ad hoc treatments for the solid walls, the main problem consists in the fact that CT scans do not allow its precise reconstruction. Sometimes considering the boundary of the nasal cavity as a solid, rigid wall is mentioned as being not entirely realistic an assumption, especially when the simulation is unsteady. Although this effect is not negligible in principle, we believe that its influence on the results is deemed to remain small, and certainly not worth the huge increase in complexity that a simulation with a full description of the mechanical fluid-wall interaction would require.

2 Interpreting the results of the simulation

5

Once the time-consuming numerical simulation has terminated (a process which may take from several hours to several days or weeks), the major problem to be addressed is how to use the sheer amount of data produced, and how to distil it into some information of true clinical use. When CFD is applied to engineering problems, its output is typically compared to results obtained with experimental tests carried out in a wind tunnel, or similar. In a sense, CFD is an in vitro information, to be assessed against in vivo data. In the particular field of interest here, such in vivo data cannot be obtained with the required detail and reliability. The few available studies based on in vivo measurements, typically based on rhinomanometry, provide just a very limited set of global quantities (like the flow rate, for example) to characterize the flow. Very recently one potentially interesting alternative is arising: it consists in creating a geometric model of a particular patient's nasal cavities, possibly enlarged by a scale factor, then building an experimental system around it to circulate a fluid inside it to the aim of measuring the local and instantaneous fluid velocity, for example via the PIV (Particle Image Velocimetry) technique. This is achieved by illuminating a plane of interest by a high-energy pulsed laser sheet. Examples of this approach, that we believe will develop in the near future, are the works by Spence et al and by Na et al [29- 31]. This paves the way to an accurate and reliable validation of the CFD results that have been up to now only assessed in terms of global quantities.

Even after a thorough validation is carried out, for the output of a reliable CFD simulation to be clinically useful it remains to be assessed how the various physical quantities (velocity, pressure, temperature, humidity) relate to the well-being of the patients. This is an additional required step towards the ultimate goal of using CFD-generated information to help the surgeon plan patient-specific actions. Several comments on this topic can be found in the review paper by Leong et al [2], as well as in that by Zhao and Dalton [32]. The former in particular highlights the primal importance of the temperature gradient in how the patient feels the airflow.

Future developments and conclusions

In the previous sections, we have attempted to illustrate the potential of CFD in the ENT world, as well as the most critical aspects that still prevent its widespread use in clinical practice. The tremendous developments in computing power and CFD techniques in the recent years are making a scenario possible where CFD will play a major role in the daily clinical practice of ENT surgeons. Clinical applications of CFD in the ENT field are potentially wide, and the information obtained from these studies will have important implications in rhinology. Unfortunately CFD has not yet succeeded in affecting the clinical practice.

In the near future, we expect precursory CFD studies to increase more and more in number, and to gradually address those shortcomings. In particular, our feeling is that the importance of considering the entire respiratory cycle instead of a simple steady inspiration or steady expiration will become widely recognized. The role played by laboratory

6

experiments in the validation of the important details of the CFD studies will become more and more prominent, as well as further enhancements in the fidelity of the physical model that is simulated numerically by the computer (e.g. including the mucosal lining, or accounting for at least some of the mechanical properties of the boundary defining the nasal airways, thus improving upon the simple solid wall model to allow at least some fluid-structure interaction). A further and potentially interesting subject of study resides in better understanding the relationship between CFD results obtained starting from CT scans and similar results obtained with RMN. Most of the available studies employ CT scans, but some based on RMN are available [14], and a critical comparison would be most welcome.

The most important comment we offer here, however, concerns a critical improvement that is needed by the whole CFD procedure to become of real clinical value. So far, such a study is way too complex and time-consuming to be truly usable in the clinical practice. Identifying the weak spots in this respect, redesigning the procedure or parts thereof, choosing and laying down any little procedural step to the aim of minimizing the total cost (to be intended in the most general sense) is at the same time an exciting challenge for a team that must include CFD experts and ENT surgeons, and an essential step towards making CFD a reality in nose surgery.

CONFLICT OF INTEREST

All Authors state that they have no conflict of interest.

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7

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8

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9