Quantification of aerosol deposition in the upper airways: A multimodality study

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Introduction

One of the key challenges in the study of health-related aerosols is predicting and monitoring sites of particle deposition in the respiratory tract. Scintigraphy is the only current method that combines quantification and regional localization[1] of aerosol deposition, but this technique remains limited by its spatial and temporal resolutions and by patient exposure to radiation. Recent work in MRI has shed light on techniques to quantify micro-sized magnetic particles in living bodies by the measurement of associated static magnetic field variations[2]. With regard to lung MRI, hyperpolarized helium-3 may be used as a tracer gas to compensate for the lack of MR signal in the airways, so as to allow assessment of pulmonary function and morphology[3,4]. The extrathoracic region of the human respiratory system plays a critical role in determining aerosol deposition patterns as it acts as a filter upstream from the lungs. Gas flow and aerosol deposition within this region can be effectively characterized by fluid and particle mechanics, and corresponding realistic rigid geometries can be constructed to experimentally validate numerical simulations. In the present work, aerosol deposition in a mouth-throat phantom measured using helium-3 MRI was correlated with computational fluid dynamics (CFD) simulations and gamma scintigraphy.

Materials and methods

Experiments were performed in a 3D mouth-throat phantom with a double labeled solution. MR superparamagnetic contrast agent (Cliavist®, Schering AG, Germany) and Technetium-99m were mixed into saline (0.9% NaCl). It was then nebulized using an ultrasonic device (Devilbiss-35-B, Washington DC, USA). To achieve deposition, nebulized aerosol was drawn through the phantom at 30 L·min^{-1} for 10 minutes. SPECT (Symbia®, Siemens Medical, Germany) was performed immediately after the aerosol deposition. The total scan time was 30 min for a 2.4×2.4×2.4 mm^3 voxel size. Known concentrations of ^{99m}Tc and superparamagnetic agent in the double labeled solution allowed quantification of iron deposition as a function of the activity detected by SPECT. Hyperpolarized helium-3 MRI was performed at 1.5 T (Achieva®, Philips Medical Systems, The Netherlands) after a two-day activity decay. Magnetic field maps were acquired using a 3D gradient-echo sequence with 4 interleaved echoes and increasing echo times TE=2.6, 22.6, 42.6, 62.6 ms. Total MR scan time was 1 min for a 4×4×4 mm^3 voxel size. A reference scan was also performed on the phantom without any iron deposition to acquire a reference magnetic field map, which then could be subtracted to reconstruct maps of the magnetic field, B_{Fe}, induced by the iron aerosol distribution only. From these magnetic field maps, it was possible to deduce the spatial distribution of aerosol droplets, their positions and weights, on the inner walls of the phantom. CFD simulations were performed with Fluent® (ANSYS, Inc., USA) following the assumption of a one-way coupling between the droplet and fluid mechanics. The boundary conditions consisted of a homogeneous velocity profile at the inlet and a free condition at the outlet. 2400 particles homogeneously distributed were injected at the inlet for 17 different diameters spanning the measured droplet size distribution. The particle trajectories were calculated by solving the equation of motion for the particles including gravity and drag forces.

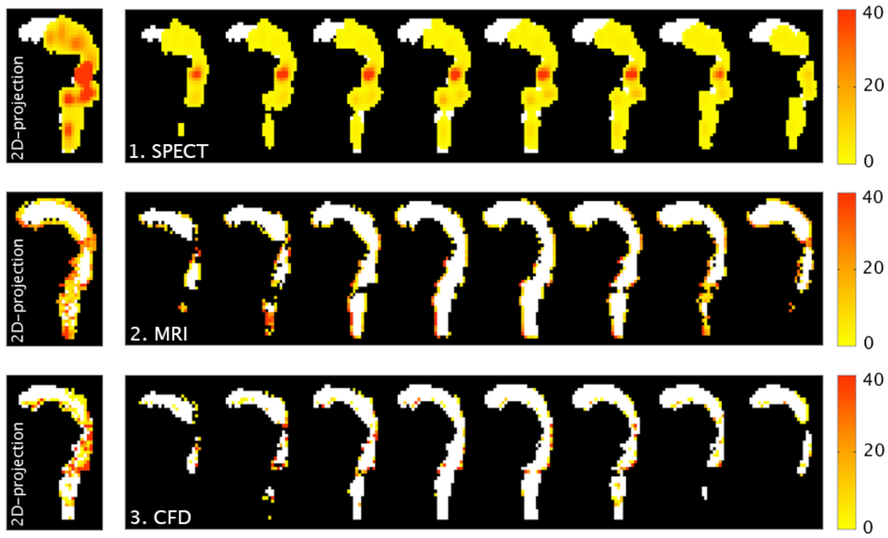

Figure 1: 3D maps of deposited aerosol (color coded µg of iron) in the mouth-throat phantom computed from 1. Scintigraphy activity maps 2. MRI static magnetic field variation maps 3. CFD simulations. The maps are superimposed onto the numerical phantom (white). 2D projections (left) and eight central slices (right) are shown.

Results

Figure 1 shows the maps of deposited aerosols (in µg) as they can be inferred from scintigraphy (1), MRI (2), and CFD (3). The total mass of iron deposited in the cast was found to be 2.5 mg and 2.3 mg for the scintigraphy and MRI data sets, respectively.

Discussion

The deposition of a double-labeled, nebulized solution was simulated with CFD and performed in a realistic mouth-throat phantom. 3D distributions of the deposited iron were processed using scintigraphy, MRI and CFD modalities. The results agree regionally and they all point out major sites of deposition at the epiglottis, the larynx, the anterior trachea, and minor initial deposition at the mouth entrance. Despite a smaller voxel size, scintigraphy suffers from a large point spread function, which led here to an effective spatial resolution higher than 5.6×5.6×6.8 mm^3 such that activity was recorded not only along the wall but also inside and outside the cast. Hyperpolarized helium-3 MRI offers spatial resolutions – down to 2×2×2 mm^3 in [5] – which allow actual 3D mapping of aerosol deposition in the airways. As the technique required no exposure to radiation, it could be further developed as an *in vivo* reference tool to probe aerosol deposition in human airways.

References

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