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Development of a 4D numerical chest phantom with customizable breathing

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ABSTRACT

Respiratory movement information is useful for radiation therapy, and is generally obtained using 4D scanners (4DCT). In the interest of patient safety, reducing the use of 4DCT could be a significant step in reducing radiation exposure, the effects of which are not well documented. The authors propose a customized 4D numerical phantom representing the organ contours. Firstly, breathing movement can be simulated and customized according to the patient's anthroporadiametric data. Using learning sets constituted by 4D scanners, artificial neural networks can be trained to interpolate the lung contours corresponding to an unknown patient, and then to simulate its respiration. Lung movement during the breathing cycle is modeled by predicting the lung contours at any respiratory phases. The interpolation is validated comparing the obtained lung contours with 4DCT via Dice coefficient. Secondly, a preliminary study of cardiac and œsophageal motion is also presented to demonstrate the flexibility of this approach. The application may simulate the position and volume of the lungs, the œsophagus and the heart at every phase of the respiratory cycle with a good accuracy: the validation of the lung modeling gives a Dice index greater than 0.93 with 4DCT over a breath cycle.

1. Introduction

The ICRP (International Commission on Radiological Protection) phantoms are continuously evolving and being refined through research. Indeed, various mathematical phantoms, such as MIRD [1], have been used since 1969. Nevertheless, they were hermaphrodite and nothing existed for children. Therefore, new phantoms appeared, [2,3], refining the organ representation. Nowadays, the ICRP uses voxelized phantom references based on computed tomography images [4], to resemble as closely as possible, the shapes, volumes and weights of various organs.

In parallel to ongoing research regarding phantoms, respiratory movement is also a growing research topic. In 2005, Low et al. estimated respiratory movement using a 5-dimension modeling representing object coordinates, current volume and airflow [5–7]. Other models also exist: in 2010, Eom et al. [8] developed a simulation based on the pressure-volume relationship linked to a finite element analysis; Vandemeulebrouke et al. [9,10] introduced the PoPi model, which relies heavily and *a priori* about the movement, since it is built using a 4DCT of the patient. The motion estimation is computed by comparing the images obtained at each respiratory phase with a simulated sequence (built using the spatial registration of images correlated with a cyclic model of breathing). It is also possible to simulate, almost in real time, respiratory movement customized to every patient, using neural networks [11]; and to use external surrogate monitoring to drive a tumor movement model ([12]). Consequently, phantoms tend to take motion into account to obtain a simulation both accurate and as close as possible to physiologic reality. Segars integrated a module for cardiac deformation into his NCAT model [13,14]. Furthermore, respiratory simulation was implemented, but remains quite limited: it mainly consists in lung deformations and translation/rotation of other organs, such as the liver and kidneys. Respiratory simulation also exists in the XCAT phantom, which relies mainly on lung deformation. This deformation is parametrized using two curves, which offers high flexibility but requires an expert to adapt it for a given patient [15].

Respiratory movement is useful for radiation treatment: a customized breathing phantom associated with patient monitoring during a treatment session allows for detailed monitoring of received doses and could lead to treatment adjustment.

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Nevertheless, from a radiation protection point of view, 4DCT provides movement information at the cost of increasing patient exposure to radiation (around 30 times the annual natural exposure). Moreover, due to technical limitations, the data may be inaccurate and contain artifacts (classification problem for example). In this context, using a customized simulation for breathing offers advantages for both radiation protection, by limiting the use of 4DCT that could be a significant step in avoiding small doses, whom effects are still not well documented; and for radiation treatment, by providing movement information for more accurate treatment planning as well as monitoring the dose actually delivered during a treatment session via the breathing cycle recorded from the patient.

Using Artificial Neural Networks (ANN), we proposed two methods: for the simulation of pulmonary movement [11], and for the adaptation of the IRSN (French radiation protection and nuclear safety institute) phantoms [16,17]. These two projects aim at developing adapted tools for a customized and accurate modeling of the human body, either in a radiation protection context (anthroporadiametry), or for delivering external beam treatment more accurately. In radiation therapy, ANN has recently been used to simulate the tumor movement according to external position trackers [18,19].

In this paper, our contribution includes a new customized phantom model that simulates realistic respiratory motion of the lungs. The breathing cycle is simulated and validated using 4DCT data. The Dice indices are computed for every respiratory phase Section 3. We also present some preliminary results for simulations of cardiac and œsophageal motion (Section 4).

2. Method: ANN presentation

2.1. The neural network

The NEMOSIS (NEural NEtwork MOtion SImulation System) platform has been presented and validated in previous work [11]: using an artificial neural network, it is possible to simulate pulmonary movement customized per patient. Nevertheless, customization was limited by a small amount of patient data, resulting in small learning sets. Moreover, only the internal anatomic structure of the lungs was considered. In this platform, a multi-layer perceptron with one hidden layer is trained using supervised learning. The synaptic weights and biases are optimized to minimize the mean squared error (MSE) using the gradient based Limited-memory Broyden–Fletcher–Goldfarb–Shanno method (L-BFGS) [20] combined with the Wolfe linear search [21] to determine the optimal step size. Moreover, 1000 iterations are performed beyond the minimum MSE to prevent overfitting by checking that a degradation is observed on the interpolation of the generalization set. An incremental approach determines the optimal number of neurons in the hidden layer [22]. The application of NEMOSIS to anthropomorphic phantoms requires several adjustments:

- Adding more patient data to the learning set via collaboration with Besançon CHRU.
- Adding the overall lung contours to the data (for 8 patients over 16).
- Modification of the ANN to improve the customization and compatibility with the IRSN phantoms : find relevant characteristics of the lung to be used as ANN entries.

The IRSN phantoms were generated by proportionally adapting an initial model for various heights [23,24]. Nevertheless, the analysis and the comparison between patient data and the phantoms demonstrated differences between real and theoretical morphologies. To represent the size of the lungs in the Superior–Inferior axis (SI axis), we take into account the size of the right lung (which is independant of the heart). The measures on the Anterior–Posterior axis and Left-Right axis (AP and LR axes) are performed along the axial plane of the carina to allow reproducibility in all patients and phantoms. Using these two axes, we have approximated the lung bounding box by using a cylinder generated by an ellipse. The ellipse perimeter P ($P = \Pi\sqrt{2\left(\left(\frac{d_{AP}}{2}\right)^2 + \left(\frac{d_{LR}}{2}\right)^2\right)}$) is presented in the last column of the Tables 1 and 2. This bounding box is used as an ANN entry.

Tables 1 and 2 are sorted according to pulmonary volume. Table 1 shows that there is no correlation between patient height and lung volume. For example, a person measuring around 1.65 m can have a pulmonary volume of 2.53 l (163 cm) or 4.15 l (165 cm). Similarly, the size of the lungs along the vertical axis (i.e. SI axis) is not a linear function of height. Nevertheless, pulmonary volume can be represented by the volume of the aforementioned cylinder. The ANN concept is extensively described in the literature [25]. The entries of the ANN are raw data to avoid biasing the learning. Therefore, the existing entries (3D coordinates of a point (its location along the 3 axis X, Y and Z), pulmonary volume, and respiratory phase) have been complemented by three new ones, which represent an approximation of the real pulmonary volume by a cylinder, i.e. the dimensions along the SI, AP and LR axes. Unfortunately, we note that the dimensions along the AP axis for all the phantoms are inferior to the patient's. As already stated [11], NEMOSIS is an interpolator *inside* the definition domain of the training data. Since the learning step is performed using patient data, the dimensions along the AP axis cannot be used for simulation on the phantoms. Therefore, the entries using the dimensions along AP and LR axes are replaced by the perimeter. Moreover, the perimeter is correlated with chest size and thus can be "externally" measured. Only phantoms with a height greater than 173.18 cm are included in the definition domain; thus, further studies are limited to these phantoms. Ultimately, 7 variables constituted the entries of the NEMOSIS ANN:

- 3D point coordinates.
- Pulmonary volume.
- The cylinder perimeter.
- The dimension of the right lung (i.e. the cylinder height), and
- The respiratory phase.

In other words, given the external measurement of a person and the desired respiratory phase, the network can simulate the corresponding customized lung contours.

2.2. The training data

The learning set for pulmonary movement was constituted by 4DCT images of 15 patients acquired during free breathing and sorted into 5 phases by the 4DCT. Firstly, on every 4DCT, positions of anatomic points are manually defined by experts and tracked over various respiratory phases, for a total of 4680 points (10 phases per patient). These points are internal characteristic locations within the lungs that are recognizable over the phases (e.g. vessels, bronchus unusual junctions). Since the IRSN phantoms consist of the organ contours only, an algorithm (region-growing) has been implemented to automatically extract the lung contours of the patients on every 4DCT. Indeed, there is no visual reference to identify a point over phases, so we take advantage of parametric curves:

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