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Statistical characterization of noise for spatial standardization of CT scans: Enabling comparison with multiple kernels and doses

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ABSTRACT

Computerized tomography (CT) is a widely adopted modality for analyzing directly or indirectly functional, biological and morphological processes by means of the image characteristics. However, the potential utilization of the information obtained from CT images is often limited when considering the analysis of quantitative information involving different devices, acquisition protocols or reconstruction algorithms. Although CT scanners are calibrated as a part of the imaging workflow, the calibration is circumscribed to global reference values and does not circumvent problems that are inherent to the imaging modality. One of them is the lack of noise stationarity, which makes quantitative biomarkers extracted from the images less robust and stable. Some methodologies have been proposed for the assessment of non-stationary noise in reconstructed CT scans. However, those methods focused on the non-stationarity only due to the reconstruction geometry and are mainly based on the propagation of the variance of noise throughout the whole reconstruction process. Additionally, the philosophy followed in the state-of-the-art methods is based on the reduction of noise, but not in the standardization of it. This means that, even if the noise is reduced, the statistics of the signal remain non-stationary, which is insufficient to enable comparisons between different acquisitions with different statistical characteristics. In this work, we propose a statistical characterization of noise in reconstructed CT scans that leads to a versatile statistical model that effectively characterizes different doses, reconstruction kernels, and devices. The statistical model is generalized to deal with the partial volume effect via a localized mixture model that also describes the non-stationarity of noise. Finally, we propose a stabilization scheme to achieve stationary variance. The validation of the proposed methodology was performed with a physical phantom and clinical CT scans acquired with different configurations (kernels, doses, algorithms including iterative reconstruction). The results confirmed its suitability to enable comparisons with different doses, and acquisition protocols.

1. Introduction

Quantitative imaging (QI) is the process of reducing functional, biological and morphological processes to a measurable quantity by means of medical imaging. The uses of QI are even greater in the light of a new healthcare delivery system that becomes more personalized and tries to tailor therapies to the underlying pathophysiology.

QI includes the development, standardization, optimization, and application of structural, functional, or molecular imaging acquisition protocols, data analyses, display methods, and reporting structures, as well as the validation of QI results against relevant biological and clinical data. This way, QI contributes to the radiological interpretation by assessing the degree of a given condition (Buckler et al., 2011; Abramson et al., 2015). QI has been adopted in clinical studies and trials to obtain more sensitive and precise endpoints. The advancement in techniques to automatically interpret and quantify medical images have been recognized by regulatory agencies that have now proposed guidelines for the qualification of image-based biomarkers to be used as valid endpoints in clinical trials (e.g. the Quantitative Imaging Biomarkers Alliance (QIBA) at www.rsna.org/qiba). The utility of quantitative imaging is somehow hampered by the lack of standardization among vendors due to the nuisances of the acquisition and reconstruction processes such as signal-to-noise ratio, spatial resolution,

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slice thickness, image reconstruction algorithms among others (Mulshine et al., 2015).

Computerized tomography (CT) is recognized as a very suitable and widely adopted modality for quantitative imaging due to its high contrast and physical interpretability of the acquired signal. Uses of the quantitative imaging in CT (qCT) are the assessment of tumor size and texture (Aerts et al., 2014), calcifications (Agatston et al., 1990), emphysema (Müller et al., 1988), stenosis (Boogers et al., 2010) to name a few. In all cases, there is a reliance on the statistics of the CT signal to derive a valid quantity that captures the pathological process.

Although CT scanners are calibrated as part of the imaging workflow, the calibration is circumscribed to global reference values of air and water (Millner et al., 1978). This fact jointly to other inherent factors of the acquisition makes the CT signal more variable than desired (e.g. photon starvation, partial volume effect, beam hardening) (Hsieh, 2003). These effects are particularly important to create a quantitative metric that is consistent among vendors and free of confounding factors due to changes in patient weight and size to fulfill requirements of accuracy and precision (Uppot et al., 2007).

Among all those issues, CT noise is an important factor that has been carefully studied during the last decades at the detector level as part of the transmission process (Whiting, 2002; Whiting et al., 2006). The non-monochromatic nature of the X-ray signal, the amount of total X-ray energy defined by tube current coupled with the effects of the reconstruction and the interaction between X-ray and matter within the scanning field of view make the noise characterization in the reconstructed image a complex process. One of the main consequences of this complexity is the lack of stationarity. It is well understood that fan-beam tomography introduces nonstationary frequencies components and nonstationary noise (Zeng, 2004) by the nature of the scanning geometry. Several methods have been developed to assess the CT noise spectrum in nonstationary conditions (Borsdorf et al., 2008a; Balda et al., 2010; Baek and Pelc, 2010).

Borsdorf et al. (2008a) proposed a non-stationary estimation of noise based on an analytical propagation of the variance throughout the whole reconstruction process (involving interpolations, convolutions, and backprojection) (Borsdorf et al., 2008b). This method provides an estimate of the variance of noise which is further decomposed into vertical and horizontal components to get the anisotropic behavior of noise in the fan-beam reconstruction. The main limitations of this method are the need of a calibrated physical noise model to estimate the noise variance in the fan-beam projections and the need of the raw fan-beam projections that are not typically available after reconstruction. Besides, although the variance is split into two different components (vertical and horizontal), they are assumed to be independent and thus, the method does not provide a truly anisotropic description of noise. The anisotropic limitation is partially avoided in Borsdorf et al. (2009), where the preferred direction is estimated as the direction with the strongest correlation during the backprojection of variance contributions.

It is important to note that the philosophy adopted in Borsdorf et al. (2008a, 2009) is not to provide a comparable level of noise between regions of the same image or even different acquisitions but to reduce the noise from direction estimates of its variance. This means that even with a noise reduction, the non-stationary behavior of noise remains active in the filtered image. This fact evidences that reducing non-stationary noise does not provide a solution for quantitative CT analysis in terms of enabling comparisons between different acquisitions that may show different statistical characterization.

A different approach was adopted by Balda et al. (2010) to provide not only the propagation of noise variance throughout the reconstruction process but also the noise power spectrum. The statistical model that describes the attenuation levels is assumed to be known (following a model or by calibration measurements). Then, certain equally distributed noise is generated with the parameters of the location under study that is reconstructed. The result is a patch with a stationary noise with the estimated noise power spectrum. This approach strongly depends on the underlying noise model adopted for the attenuation observed in the detector. Thus, the noise power spectrum can be substantially biased in scenarios where the underlying model differs due to the response of polychromatic X-ray beams. Besides, the fan-beam projections are required to estimate the noise power spectrum. This methodology provides a way to compare acquisition protocols for CT scanners from different manufacturers when comparing the reconstruction over the same phantom (matching different reconstruction kernels). However, it does not provide a suitable way to enable comparisons between different acquisitions.

Recently, Kim et al. (2016) proposed a methodology based on the IMPACT iterative reconstruction algorithm (Man et al., 2001). That reconstruction method allows the calculation of the local variance in each iteration that can be used to transform the non-stationary noise to a more treatable one. A functional relationship between local variance and local mean is imposed by considering a *conversion factor* defined as the local mean divided by the local variance, which is multiplied to the reconstructed image. Then, the resulting random variable is assumed to have a linear dependence, which can be used to transform the noise distribution to a Gaussian one. Finally, any optimal filter for stationary Gaussian noise can be applied for noise reduction and the transformation is inverted to obtain the denoised image.

The method proposed by Kim et al. (2016) offers an interesting perspective to deal with non-stationary noise. However, it requires the raw data projections before the reconstruction, which are not usually available in standard clinical routine. Besides, the calculation of local statistics is also required. This calculation was done considering identically distributed samples in the local region. This is a strong assumption that obviously provides biased results in locations with different attenuation levels, especially at the edges.

Summarizing, the methods mentioned above show common inconveniences to provide a unifying framework to enable comparisons between images acquired in different conditions:

- They require the projection information from the detectors. That information is not available in all studies.
- They are not designed to address other sources of nonstationarity like changes in the transmission medium due to different body weight distributions.
- They are focused on the noise reduction. The resulting images are still not comparable after noise reduction; the noise remains non-stationary.
- They do not provide a statistical characterization of noise after processing.

In this paper, we propose a complete methodology to avoid these limitations. With this aim, we circumvent the need of projection information by proposing a statistical characterization of noise in the images after reconstruction. The proposal is supported by a statistical exploratory analysis of reconstructed images with different configurations including dose, reconstruction kernels, and manufacturers. As a result, we propose a non-central Gamma as the probabilistic distribution that describes the statistical behavior of noise in all the different situations.

The probabilistic distribution is used to define a statistical mixture model that allows us to account for the partial volume effect in the description of local noise characteristics. The full methodology to estimate the local probabilistic characterization of noise throughout the image is also derived.