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ANALYSIS OF ITERATIVELY RECONSTRUCTED CT DATA: NOVEL METHODS FOR MEASURING IMAGE QUALITY

ANALÝZA ITERATIVNĚ REKONSTRUOVANÝCH CT DAT: NOVÉ METODY PRO MĚŘENÍ OBRAZOVÉ KVALITY

DOCTORAL THESIS - PREVIEW
TEZE DIZERTAČNÍ PRÁCE

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ABSTRACT

The collective dose from medical radiation has been sharply increasing as well as availability of CT scanners and increasing number of indicated pathologies. Hence, reduction of applied dose is a topical theme nowadays. A great progress has been made by introduction of novel iterative methods for reconstruction of image data from measured projections. A new interest and need for CT image quality measurement have been simultaneously reported. Quality of iteratively reconstructed data was so far quantitatively measured in phantom scans or in small regions of interest in real patient data. However, the character of iteratively reconstructed data suggest that those approaches are no longer sufficient and they need to be revised or replaced by a new ones. Design of novel CT image quality parameters which will respect specifics of iteratively reconstructed data and will be fully automatically computed directly from real patient data is the main objective of this thesis.

KEYWORDS

X-ray CT imaging, Image Quality, Iterative reconstruction, Noise power spectrum.

ABSTRAKT

Se zvyšující se dostupností medicínského CT vyšetření a s rostoucím počtem patologických stavů, pro které je indikováno, se redukce pacientské dávky ionizujícího záření stává stále aktuálnějším tématem. Výrazný pokrok v tomto odvětví představují nové metody rekonstrukce obrazů z projekcí, tzv. moderní iterativní rekonstrukční metody. Zároveň se zavedením těchto metod vzrostla potřeba pro měření obrazové kvality. Kvalita iterativně rekonstruovaných dat byla doposud kvantitativně hodnocena pouze na fantomových datech nebo na malých oblastech zájmu v reálných pacientských datech. Charakter iterativně rekonstruovaných dat však naznačuje, že tyto přístupy nadále nejsou dostatečné a je nutné je nahradit přístupy novými. Hlavním cílem této dizertační práce je navrhnout nové přístupy k měření kvality CT obrazových dat, které budou respektovat specifika iterativně rekonstruovaných obrazů a budou počítána plně automaticky přímo z reálných pacientských dat.

KLÍČOVÁ SLOVA

Rentgenová výpočetní tomografie, obrazová kvalita, iterativní rekonstruce, šumové výkonové spektrum.

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INTRODUCTION

The collective dose from medical radiation has been sharply increasing. Irradiation of the population from computed tomography (CT) examinations is increasing and comprises approximately 30% of the radiation burden from all radiodiagnostic methods [5]. In order to be compliant with the ALARA (as low as reasonably achievable) principle, each of the major CT manufacturers have focused their research on as large radiation dose reduction as possible. As a result of this increased effort, many new strategies for reducing radiation dose have been introduced. Among a range of dose reduction methods the iterative reconstruction takes an exceptional position by producing high quality images, even when drastic radiation dose reduction (up to 70%) is applied [6]. Such a dose reduction is allowed by inclusion of photon counting statistics and models of acquisition process into a reconstruction.

Introduction of novel iterative reconstruction methods attracted new attention to measurement of CT image quality which is needed for their comparison with FBP. Many studies dealing with problem of image quality evaluation of iteratively reconstructed images have been proposed recently. These studies are targeted either to assessment of image quality in small regions of interest in real patient data [10] or to evaluation of images acquired by scanning of phantoms [11]. Both approaches are suboptimal even for data reconstructed by FBP. The former approach utilizes information only from very spatially limited range of a data and the phantom approach analyzes noise properties in homogeneous regions of artificial images and there is difficulty to relate obtained results to clinical practice. Moreover, novel iterative reconstruction methods are generally nonlinear which, for example, causes that noise in iteratively reconstructed data is, according to [12] and [13], object dependent (i.e. its characteristics depend on density of imaged tissue). This effect can not be observed in data reconstructed by FBP. Evaluation of noise properties in homogeneous parts of water filled phantom is, hence, unable to capture whole complexity of noise in real patient data reconstructed by iterative methods. The main objective this thesis is, thus, to design novel fully automatic approaches for measuring image quality which will be more convenient for iteratively reconstructed data.

As already mentioned, all main CT vendors introduces their own algorithms for modern iterative reconstruction. Two iterative reconstruction methods were developed by Philips company; first statistical iterative method is called iDose^4 and second model based iterative reconstruction is called IMR. Prototypes of both reconstructors were lend to the Children's Hospital for long time data acquisition and early (prior to introduction of both methods to the market) image quality evaluation. The data acquisition as well as objective and subjective evaluation of image quality, can be divided into two stages. In the first stage (within this thesis called "The iDose^4

project") a prototype of iDose^4 were available and a large set of 207 scans were acquired. Quality of the acquired data were evaluated both subjectively (results of subjective medical evaluation were published in [7]) and objectively as described in this thesis.

According to information provided by the vendor, iDose^4 significantly reduces image artifacts and noise. Based on phantom measurements, it is also declared that iDose^4 do not significantly alter noise texture (which is determined by noise frequency properties) and, thus, preserves natural look and feel of conventionally (i.e. by FBP) reconstructed images (radiologists are used to diagnose from images with FBP-like noise). In order to examine whether this positive attribute of iDose^4 applies also to real patient data, a methodology for estimation of noise frequency properties from real patient data and moreover from separate tissues is proposed. The second proposed image quality measurement, thus, compares frequency properties of noise in images reconstructed by FBP and iDose^4 and evaluates noise spectral shifts introduced by iterative reconstruction. The proposed methodology allows also comparison of frequency properties of noise which is typical for diverse tissues.

A data preprocessing necessary for "The iDose^4 project" is described in Sec. 1.1 and Sec. 1.2. Evaluation of noise in real patient data is problematic especially due to inability to fully automatically distinguish between anatomical structures and image noise patterns as it is possible in homogeneous parts of scanned phantoms. However, this problem is solved by subtraction of differently reconstructed data (the fact that iDose^4 method influences only artifacts and image noise whereas anatomical structures remains mostly untouched is utilized) and by a method for determination of regions of dominant radiological noise in images resulting from the subtraction presented in Sec. 2.1. Spectral properties of radiological CT noise are routinely evaluated by one-dimensional noise power spectrum (1D NPS) calculated from square noise matrices. In order to be able to calculate 1D NPS in separate tissues its computation is adapted so that it can be estimated from non-square regions which inevitably increase errors caused by spectral leakage. A novel method for spectral leakage reduction in image data utilizing two-dimensional spatially adaptive weighting functions is, also, proposed in Sec. 2.2.3.

A prototype of IMR reconstructor was tested during the second phase within this thesis called "The IMR project". Again, a large set of patient data was acquired and their quality were evaluated objectively and also subjectively. Results of subjective medical evaluation of image quality were published in [5].

In contrast to iDose^4, IMR method is targeted not only to noise and artifact reduction, but is also able to improve spatial resolution and low-contrast resolution. Fidelity of anatomical structures reconstruction, thus, should be improved with respect to a data reconstructed by iDose^4 and FBP. An objective image quality assessment is, hence, targeted to evaluation of quality of anatomical structures reconstruction in real patient data. Anatomical structures in real patient data are not a priori known (as e.g. in phantoms for measuring of spatial resolution), evaluation of quality of their reconstruction is, thus, problematic due to lack of gold standard. Considering theoretical density of air in CT scans as -1000 Hounsfield units (HU), an exception may be represented by air filled structured like e.g. airways. The proposed criterion of quality of anatomical structures reconstruction is based on analysis of airways density. The closer the densities of airways are to the theoretical value the more quality the reconstruction is. 31 data sets acquired from thoracic body part were selected for this study and necessary lung and airways segmentation were performed which is described in Sec. 1.3. CT data reconstructed by diverse methods from a single set of projections are perfectly aligned and their direct comparison is not problematic. Problems arises when scans with different dose reduction (acquired immediately in succession, but there is always displacement e.g. by respiratory movements) have to be compared. Methods dealing with registration of CT lung data are, of course, available however an interpolation necessary for geometrical transforms may negatively influence results of the image quality assessment. A method which utilizes registration and allows comparison of corresponding airways voxels in both scans is proposed in Sec. 3.1. Results of data analyzes of the both stages are summarized in Sec. 4 and are discused in Sec. 5

1 DATA PREPROCESSING

An extensive preprocessing, which makes the real patient data quality assessment possible, was needed and is described in this section. Preprocessing necessary for the iDose^4 project can be divided into two main parts. Elimination of stair-step errors caused by defect of gantry tilt correction during the data acquisition, which is described in Sec. 1.1, is the first preprocessing step. A second step, necessary for evaluation of noise properties in diverse tissues, is segmentation of basic tissues in head CT data. The segmentation approach based on graph-cuts is presented in Sec. 1.2. Skull segmentation turns out to be problematic especially due to complicated structure of a cranial base with very weak cortical bone parts and densities of trabecular bone parts similar to densities of soft tissue.

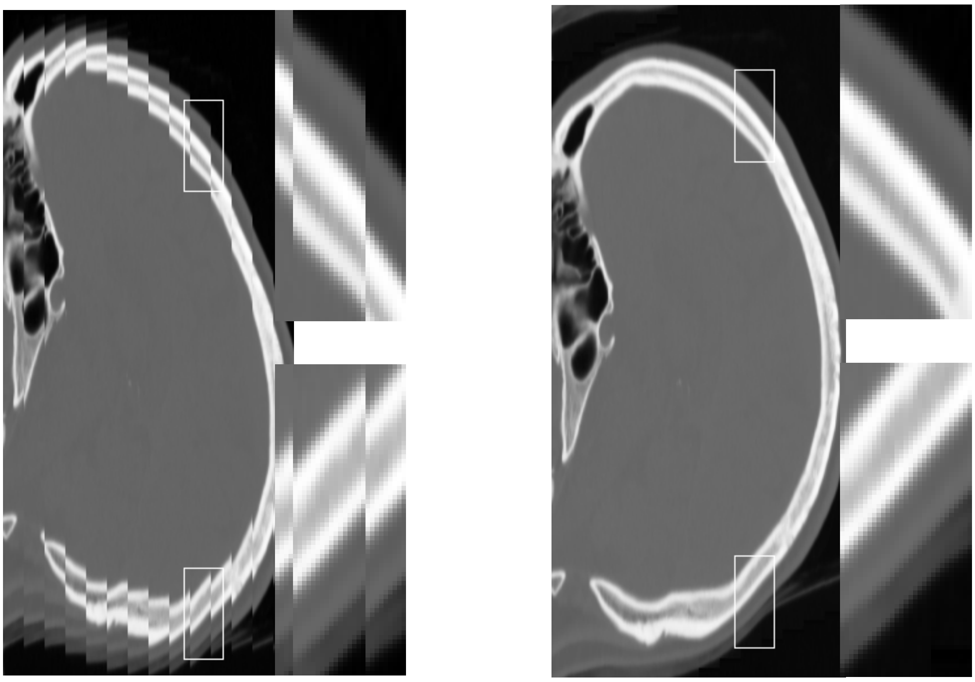
In order to be able to assess quality of different reconstruction methods via evaluation of quality of airways reconstruction (which is a main goal of the IMR project), the airways must be firstly segmented. As airways segmentation is not a crucial part of this thesis, a method inspired by [1] which is easy to implement and gives satisfactory results is used and described in Sec. 1.3. However, this method is slightly modified; morphological reconstruction is calculated directly in 3D space (instead 2D slice by slice calculation) and thresholding after morphological reconstruction (which produces airways candidates) is replaced by graph-cut segmentation.

1.1 Data Driven Gantry Tilt Correction

During the iDose^4 prototype testing, it was found that the originally acquired CT images suffered from very severe errors, which were apparent after the three-dimensional reformation to sagittal plane. These errors are caused by the defect of gantry tilt correction during tilted multi-section scanning and are reflected as mutual misplacements of data sub-volumes. The width of misplaced sub-volumes (i.e. the count of its axial slices) corresponds to the number of slices acquired during a single gantry revolution and the magnitude of shift between sub-volumes is connected to the degree of gantry tilt. This specific kind of error is called stair-step error.

Image quality (in terms of image noise content and fidelity of anatomical structures reconstruction) is not affected, and data can be fully recovered (when neglecting interpolation errors) by precise registration of sub-volumes. The stair-step error may harm (or even make impossible) further data processing or noise analyzes. Therefore, a large set of a quite unique data might become lost. A sufficiently fast data driven method for gantry tilt correction is thus needed.

Correction of stair-step error can be divided into two separate problems while the first is the detection of number of slices acquired on a single gantry revolution and the second is registration of misplaced sub-volumes.



(a) (b)

Obr. 1.1: Demonstration of stair-step error correction on a single brain image (with magnified sections): (a) Originally scanned brain data, (b) brain scan after the stair-step error correction.

The correction of stair-step error is demonstrated on the testing image Fig. 1.1a. A signal resulting from the calculation of Euclidean distance similarity measure between consecutive axial slices is used for the detection of misplaced sub-volume borders. The resulting function is called inter-slice variability (IV).

The detection of misplaced sub-volumes' borders is divided into three main steps. Firstly, peaks (both caused by anatomical variability and sub-volumes shift) are separated from the IV curve using gray-scale mathematical morphology. Secondly, the curve remaining after the peaks' separation representing slow trends is processed and the head area with low anatomical variability is detected. Peaks in the area of low anatomical variability are predominantly caused by a shift of sub-volumes and their subsequent final detection is less complicated. Considering a constant width of sub-volumes (the number of slices acquired in a single gantry revolution does not change during a particular CT scanning), it is sufficient to detect the sub-volume borders only in this area.

Once the borders of misplaced sub-volumes are known, their registration is performed in two steps. Raw shift estimation is provided by a phase correlation method

(POC) with sub-pixel precision according to [14]. This is further refined by the method based on optimization of Euclidean distance similarity criterion using a gradient method with adaptive step size. Finally corrected exemplary brain scan Fig. 1.1a is depicted in Fig. 1.1b

1.2 Segmentation of basic tissues in CT head data

	μ	σ_A	σ_B	λ	σ
Air filled structures	-270 HU	700 HU	700 HU	0.001	10 HU
Adipose tissue	-20 HU	40 HU	40 HU	10	2 HU
Bones	270 HU	80 HU	200 HU	0.1	4 HU

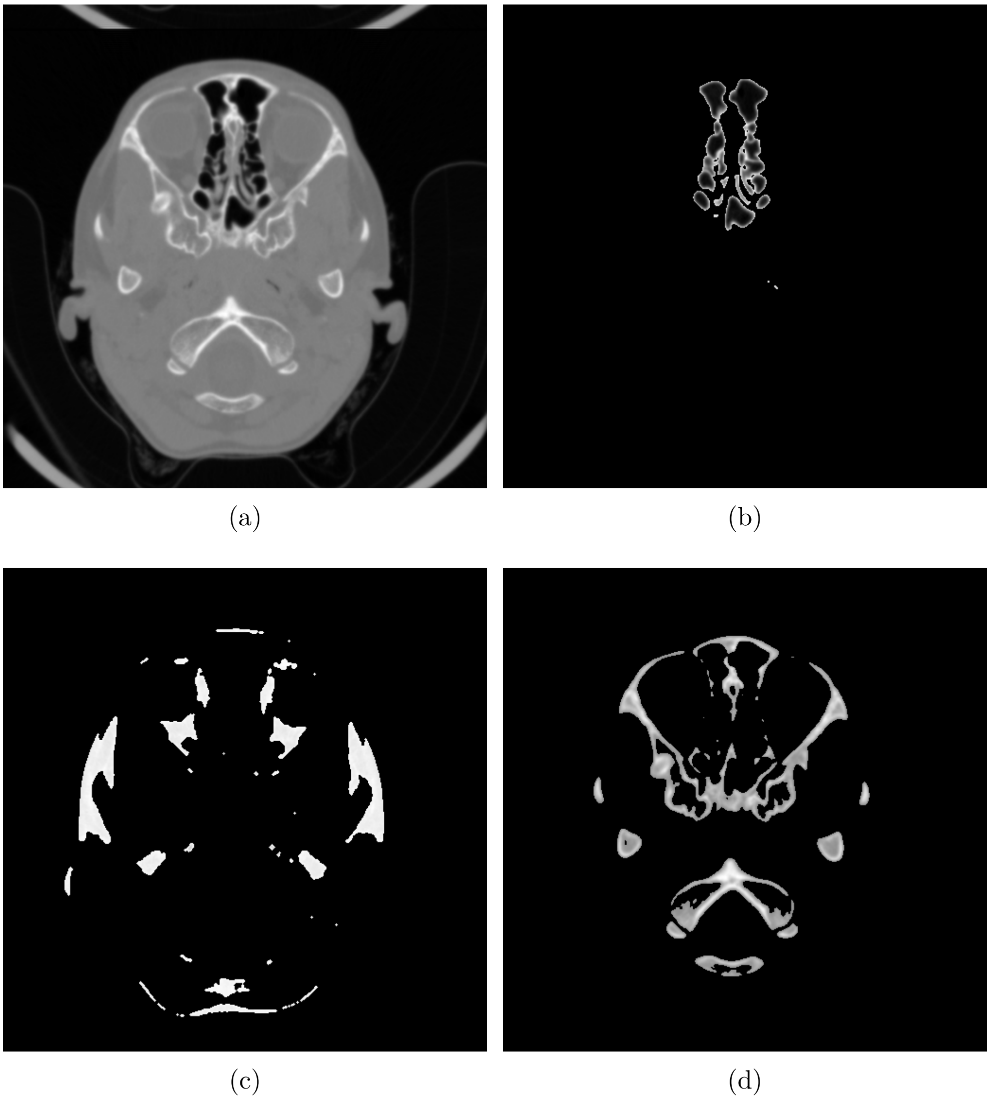
Tab. 1.1: Settings of parameters of graph cut based segmentation of basic tissues in a head CT scans.

To be able to assess noise properties separately in basic tissues of a human head (typically soft tissue, bones, adipose tissue and air filled structures like paranasal sinuses or internal auditories) an automatic and reliable segmentation algorithm is needed. Segmentation method utilizing graph-cuts [4] is used as it incorporates information not only about intensity of voxel to be classified but also about intensities of neighboring voxels.

The method requires prior knowledge in form of interactive labeling of voxels subsets taken from segmented background and object which are subsequently used for computation of corresponding intensity distributions $Pr\left(I|\mathcal{O}\right)$ and $Pr\left(I|\mathcal{B}\right)$. Thanks to the fact that positions of peaks representing tissues in histogram of CT head scan are not significantly varying among individuals (partly thanks to consistency of scanning parameters and partly thanks to the fact, that tissues of human head are not changing significantly with patient age, weight and sex), therefore, in this case, it is sufficient to set the intensity distributions as a cumulative distribution functions of normal distribution with heuristically determined means (set with respect to locations of the tissue peaks) and standard deviations. Setting of graph cut based segmentation of CT head scans is summarized in Tab. 1.1.

Skull segmentation is a challenging problem partially due to very complex structure of cranial base with thin cortical bone parts and partially due to overlapped densities of inner parts of bones (trabecular bones) and soft tissue; as can be seen in histograms of manually selected parts of both tissues in Fig. 1.3.

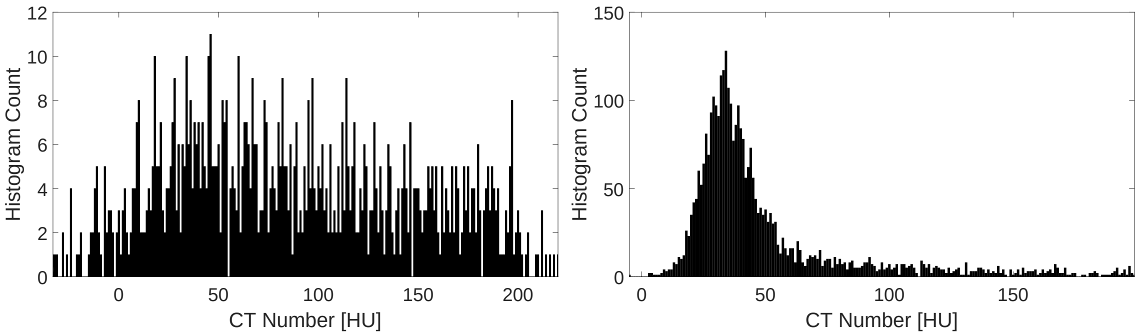
Some parts of cortical bones as well as large areas of trabecular bones parts are missing in the bones segmentation. Those imperfections are corrected in two steps;



(a) (b) (c) (d)

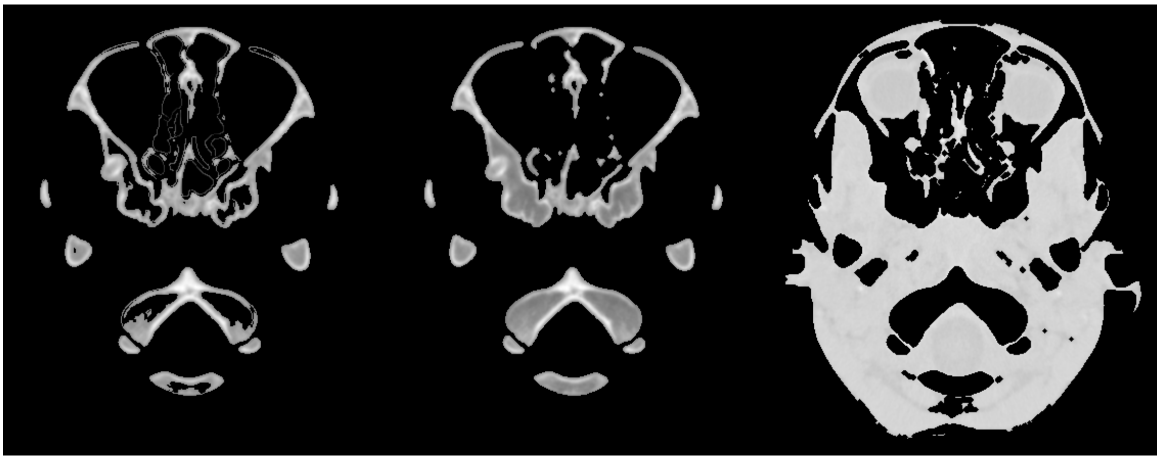
Obr. 1.2: Example of result of graph-cut based segmentation of basic tissues: (a) slice of original data; (b) segmented air filled tissue; (c) segmented adipose tissue, (d) segmented bones.

missing parts of cortical bones are, firstly, added to the segmentation using analysis of segmented contour. In the second step, so called holes (i.e. areas of zeros fully surrounded by ones in a binary segmentation mask), which may represent either trabecular bone or soft tissue, are classified utilizing differences of shape of their local histograms.



(a) (b)

Obr. 1.3: Typical histograms of manually selected parts of trabecular bone (a) and soft tissue (b).



(a) (b) (c)

Obr. 1.4: Example of correction of mis-segmented bones parts remaining after graph-cut based segmentation; example of segmentation of soft tissue: (a) example of correction of mis-segmented cortical bone parts remaining after graph-cut based segmentation Fig. 1.2d, (b) example of a final bones segmentation after adding recognized trabecular bone parts, (c) example of segmentation of soft tissue.

1.3 Airways Segmentation

The presented airways segmentation method is composed from three main steps; gray-scale morphological reconstruction is calculated several times with diverse sizes of structural element in order to enhance airways. Data after the enhancement are segmented by graph-cut method which produces binary airways candidates. The final segmentation is obtained by binary region growing with automatically determined seed.

1.3.1 Airways enhancement by gray-scale morphological reconstruction

Local minima in image data and, thus, airways which always have lower density than the surrounding tissue, are enhanced by gray-scale mathematical morphology according to [1].

The choice of structural element $H1$ fundamentally affects shape and size of objects which will be enhanced. A set of disc shaped structural elements with various diameters (21, 17, 13, 9, 5, 3) px are used in this application as majority of airways cross sections are circularly shaped and their diameters are gradually decreasing when they approach peripheral lungs parts. A set of six three-dimensional matrices with differently enhanced airways is produced in this step.

1.3.2 Segmentation of airways candidates

The next step in airways segmentation is extraction of airways candidates. Instead of thresholding like in [1] and [8], graph-cut based method is used. The enhancement with a different size of $H1$ produces a different contrast (with respect to surrounding tissues) for airways with different widths. Hence, it would be advantageous to determine μ parameter for graph-cuts adaptively for each differently enhanced data. With decreasing size of $H1$, thinner airways are more enhanced which have lower overall spatial extent. Setting of μ parameter, thus, reflects this relation. For each size of $H1$, μ is determined as a gray level in which normalized cumulative histogram of enhanced data reaches a certain value according to Tab. 1.2.

Tab. 1.2: Parameters for thresholding of moralized cumulative histograms of data enhanced by diverse diameters of $H1$, which are utilized for adaptive selection of μ parameter for graph-cut based generation of airways candidates.

Diameter of $H1$	21	17	13	9	5	3
Cum. Hist. Threshold	0.9500	0.9850	0.9875	0.9900	0.9900	0.9900

Six binary matrices containing candidates for airways are obtained after the graph-cut segmentation; a final matrix of the candidates is computed as their union, which, as is evident from volume rendering in Fig. 3.1a, contains many false detections.

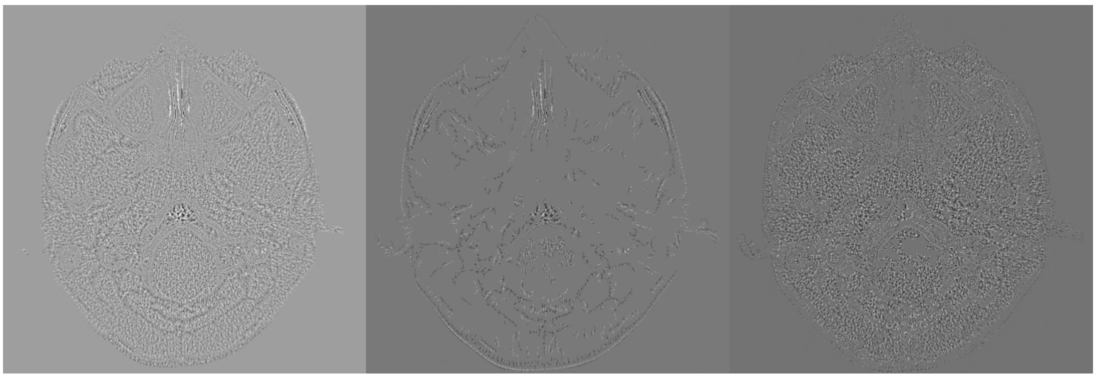
1.3.3 Elimination of the false airways candidates

Falsely detected airways candidates are mostly formed by isolated objects not connected to a airways tree. This fact is used in their elimination; each airway candidate which is not spatially connected with detected trachea origin is considered a false detection and removed. The elimination is, thus, composed of two steps; the detection of trachea origin which is subsequently used as a seed point for following 3D region growing. Final airways segmentation of 80% and 20% scans are, in the further text, denoted as S_{80} and S_{20}, respectively.

2 EVALUATION OF NOISE PROPERTIES OF DATA RECONSTRUCTED BY IDOSE^4 METHOD

Image noise is a crucial factor affecting image quality. Practically, two main types of image noise are dominant in CT data: radiological noise and streaking artifact. This study is focused only on evaluation of radiological noise in terms of its frequency properties represented by one-dimensional noise power spectrum (presented in Sec. 2.2). In order to evaluate radiological noise in real patient data, anatomical structures and areas where streaking artifact is dominant have to be removed. A methodology for determination of areas of dominant radiological noise is presented in Sec. 2.1.

2.1 Determination of regions of dominant radiological noise



(a) (b) (c)

Obr. 2.1: Detection of area of dominant radiological noise in a residual noise image: (a) a residual noise image, (b) detected directional structures, (c) detected areas of dominant radiological noise (images (b) and (c) are multiplied with the residual noise image).

Data processing which leads to determination of areas with dominant radiological noise can be divided into two steps. The first step is subtraction of an image reconstructed by FBP from an image reconstructed by iDose^4 which eliminates majority of anatomical structures. Results of the subtraction are called residual noise images.

Majority of anatomical structures are removed in the residual noise images, however streaking artifact is emphasized by the subtraction as well as edges among anatomical structures. Areas where dominant streaking artifact are, as well as remaining rests of edges, in contrast to areas of dominant radiological noise, characteristic by directionality (e.g. possibility to determine direction of stripes in areas of dominant streaking artifact). The directionality is used as a feature for detection of areas of dominant radiological noise which utilizes cascade of continuous wavelet transform with directional Cauchy wavelet and filtering with bank of oriented anisotropic Gaussian filters.

2.2 Evaluation of stability of noise frequency properties among FBP and iDose reconstructions

As already mentioned, iDose^4 reconstruction method aims at lowering the level of image noise with preservation of look and feel of conventionally reconstructed images. Preservation of frequency properties of image noise in iteratively reconstructed images, compared with the conventionally reconstructed ones, is very important for their conventional look and also for diagnostic purposes (radiologists are used to diagnose from images with FBP-like noise).

Hence, the objective of this study is to extract a parameter, which describes noise frequency properties, from real patient data and subsequently to assess how does the iDose^4 reconstruction method influence the noise spectral characteristics compared with FBP reconstruction. A 1D NPS is used, as it provides a complex spectral characteristic of radiological noise in CT data. A single parameter, center of gravity (CoG) of 1D NPS calculated according to

$$CoG = \frac{\sum x f(x)}{\sum f(x)}, \tag{2.1}$$

where x is a frequency axis normalized by a Nyquist frequency and $f(x)$ represents 1D NPS curve, is extracted from each 1D NPS. A final parameter $\overline{CoG}$ (called stability index), which serves as the measure of change of noise frequency properties among the reconstructions, is defined as

$$\overline{CoG}_{iDose} = 100\,|CoG_{FBP} - CoG_{iDose}| \tag{2.2}$$

and express percentage absolute difference between center of gravity of 1D NPS of noise in by FBP and iDose^4 reconstructed data.

Prior to evaluation of stability of noise frequency properties in real patient data, identical analysis is performed on homogeneous (water filled) areas of scanned standard CT calibration phantom where only a radiological noise is present. Results of the stability measurements performed on the phantom scans will be further used for validation of the results extracted from real patient data.

As stated in Sec. 2.1, subtraction of differently reconstructed data is an essential step in evaluation of noise properties in real patient CT data. An analysis of influence of the subtraction on the position of 1D NPS center of gravity is, thus, performed on the phantom scans. The 1D NPS CoGs are calculated from the original data (which is allowed by homogeneity of a water filled part of imaged phantom) and from subtracted data (reconstruction ID 70 is, this time, subtracted from rest of the reconstructions). Errors in CoG of 1D NPS estimation caused by subtraction of differently reconstructed noise matrices are, according to Tab. 2.1, approximately one percent of the considered frequency range.

Tab. 2.1: CoGs of 1D NPS calculated from homogeneous parts of scanned phantoms reconstructed by diverse methods. The CoGs calculated from original data are in the first row, whereas the CoGs calculated from data when a scan reconstructed by iDose^4 level 70 is subtracted are in the second row.

	FBP	ID 30	ID 50	ID 70
COG_{Orig}	0.588	0.587	0.586	0.584
COG_{Sub}	0.597	0.597	0.596	-

A similar analysis is performed for stability indexes calculated according to Eq. 2.2 again for original and subtracted noise matrices. According to the results summarized in Tab. 2.2, subtraction of a noise matrix reconstructed by iDose^4 level 70 have low impact to accuracy of stability index calculation (maximal error is 0.07 %). Residual noise images, thus, can be used for evaluation of noise frequency properties stability in real patient data.

Tab. 2.2: Stability indexes of iDose level 30 and 50 reconstructions computed from original (not subtracted) and subtracted noise matrices.

	ID 30	ID 50
$\overline{COG}_{Orig}[\%]$	0.28	0.43
$\overline{COG}_{Sub}[\%]$	0.21	0.46

Besides evaluation of errors introduced by subtraction of noise matrices, another influences have to be inspected. Firstly, original equation for NPS computation is adapted to be consistent with character of segmented residual noise images. Secondly, estimation of 1D NPS in separate tissues is inevitably loaded by errors caused by spectral leakage. Magnitudes of those errors are evaluated in Sec. 2.2.2 and a methodology for their reduction is presented in Sec. 2.2.3.

2.2.1 Simulation of MDCT noise

To be able to compute errors of 1D NPS estimation caused by tissue segmentation, a matrices filled by simulated noise with exactly known 1D NPS must be created. A matrices sized $512 \times 512 \times X$ voxels (where X stands for number of slices in a considered data) filled with zero-mean white noise are generated. The statistical noise inherent to CT data is not typically white [3]; therefore, the generated noise need to be colored (its spectral envelope must be modulated). The function for spectral envelope modulation is extracted from homogeneous (water filled) area of the scanned standard CT calibration phantom and interpolated to a desired length of 512 samples. The one-dimensional spectral modulation function is, thus, known and subsequently rotationally extended to the two-dimensional modulation function.

2.2.2 Evaluation of errors in estimation of 1D NPS forced by tissue segmentation

As already mentioned, stability indexes of iDose[4] reconstructions will be evaluated using calculation of center of gravity of tissue noise power spectrum. The objective of this section is to evaluate how are CoGs of 1D NPS influenced by tissue segmentation. The noise matrices, simulated in the previous section, have their noise power spectra exactly defined by the modulation function and the segmentation introduced errors can, hence, be evaluated. As 1D NPS center of gravity of generated noise matrix CoG_{GS} is exactly known, it serves as a gold standard. 1D NPS CoG of identical noise matrix weighted by e.g. binary mask for bones segmentation is denoted as CoG_{Bones}. Segmentation introduced error expressed in percents (SIE_{Bones}) is than calculated by

$$SIE_{Bones} = 100 \left| CoG_{GS} - CoG_{Bones} \right| . \tag{2.3}$$

Tab. 2.3: Means and standard deviations of errors in estimation of CoGs of 1D noise power spectra introduced by tissue segmentation calculated from a whole set of 33 scans.

	Soft tissue	Bones	Adipose tissue	Air filled structures
mean SIE [%]	0.204	0.404	0.959	0.973
std SIE [%]	0.035	0.106	0.403	0.375

Results of measuring of errors in CoGs of 1D NPS estimation introduced by segmentation of diverse tissues are summarized in Tab. 2.3. It can be concluded that tissue segmentation significantly influences precision of the CoGs estimation especially considering tissues with relatively low spatial extent (i.e. adipose and air filled tissues) where mean SIE is approximately 1% of considered frequency range. A methodology for SIE lowering, which, as will be shown, can potentially be useful in other applications where a frequency spectrum has to be calculated from regions with irregular shape, is presented in Sec. 2.2.3.

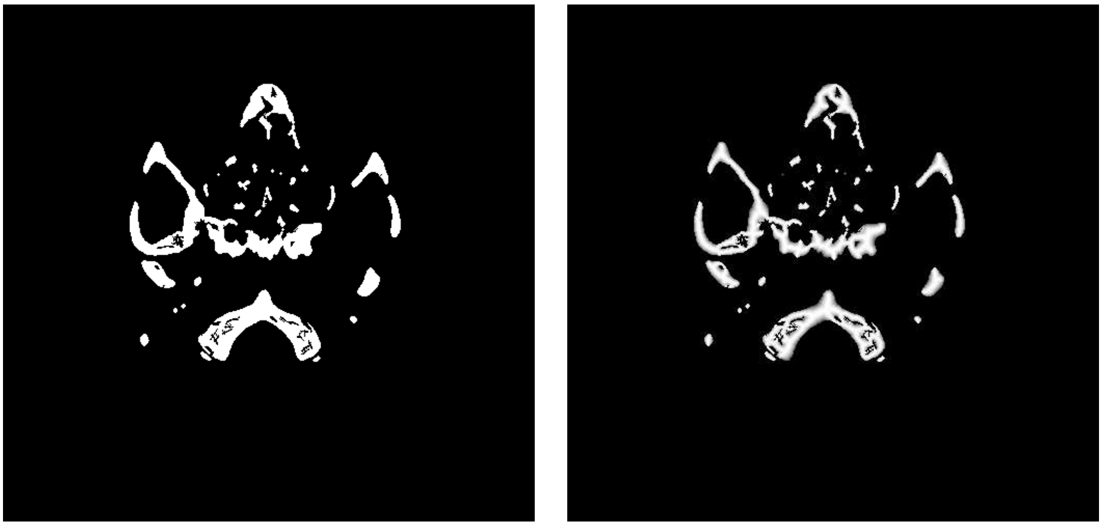
2.2.3 Two-dimensional spatially adaptive windowing functions

The errors in 1D NPS estimation caused by tissues segmentation are predominantly caused by two effects. Noise power spectra are, firstly, calculated from substantially lower number of voxels, estimation, thus, can not be precise. The second effect is spectral leakage well known from one-dimensional signal processing where shortening of theoretically infinite signal by a rectangular window cause decrease of frequency resolution as spectrum of signal is convolved with spectrum of rectangular weighting window (i.e. sinc function). Undesirable effect of leakage in spectral domain is usually reduced either by prolonging a window length or using window with better spectral properties. Analogically, a binary segmentation mask can be, in this application, viewed as two dimensional rectangular weighting window with spatially adaptive shape. Shape of a binary segmentation mask is restricted by delineation of tissues in real patient data, prolonging of window length, therefore, can not be used. Problem of reduction of effect of spectral leakage is, hence, solved by design of two-dimensional windowing functions commonly used in signal processing (e.g. Hann or Hamming) whose shape is adaptable to a the shape of a segmented binary objects. Those functions are named two-dimensional spatially adaptive windowing functions (2D SAW). Several different approaches for 2D SAW design are proposed which are based on medial axis transform calculated according to [2].

2.2.4 Improvement of segmentation introduced errors by 2D SAW application

Once the methodology for 2D SAW design is established, its impact to segmentation introduced errors in the same manner as in Sec. 2.2.2 can be evaluated. An example of 2D SAW applied to a binary mask of segmented bones is visualized in Fig. 2.2.

Results of measurement of errors in 1D NPS center of gravity estimation introduced by segmentation of diverse tissues when a Welch type 2D SAW is used are



(a) (b)

Obr. 2.2: Example of the two-dimensional spatially adaptive windowing function applied to the binary image of segmented bones: (a) binary image of segmented bones, (b) derived Welch type 2D SAW.

summarized in Tab. 2.4.

Tab. 2.4: Means and standard deviations of errors in estimation of center of gravity of 1D noise power spectra introduced by tissue segmentation after application of 2D spatially adaptive windowing functions.

	Soft Tissue	Bones	Adipose tissue	Air filled structures
mean SIE [%]	0.021	0.038	0.115	0.157
std SIE [%]	0.014	0.036	0.105	0.134

By comparison of Tab. 2.3 and Tab. 2.4 where means and standard deviations of segmentation introduced errors with and without 2D SAW utilization are shown, it is evident that, for each considered tissue, SIE rapidly decreases after 2D SAW application. Magnitudes of segmentation introduced errors are substantially lower than magnitudes of stability indexes evaluated on phantoms for soft tissue and bones (see the results in Tab. 2.2), however they are still relatively high for adipose and air filled tissues. It can, thus, be concluded that, after the 2D SAW application, measurement of stability indexes in separate tissues of real patient data is possible.

3 COMPARISON OF FBP, IDOSE^4 AND IMR METHODS BY FIDELITY OF ANATOMICAL STRUCTURES RECONSTRUCTION

As already stated, both tested iterative reconstruction methods (iDose^4 and IMR) should significantly reduce level of image noise. The main difference between them lies in fidelity of anatomical information reconstruction, which should be significantly improved by IMR method (compared to the results obtained by FBP reconstruction). The main goal of "The IMR project" is to design a CT image quality measure which would be able to assess fidelity of anatomical information reconstruction.

Evaluation of fidelity of anatomical information reconstruction in real patient data is problematic due to missing gold standard (i.e. exact and correct values of HU in tissues are not a priory known). The only exception may be represented by airways which contain only air (provided that no pathology is present) with exactly known density (-1000 HU). Another aspect which makes airways an ideal object for evaluation of fidelity of anatomical structures reconstruction is that they are composed of "tubes" with different diameters, a dependence of the quality of reconstruction on size of imaged detail may be also evaluated.

As a theoretical density inside airways is known, each positive deviation from that value is considered as decrease of image quality. A parameter describing image quality is, thus, simply mean of densities inside airways whereas the lower the mean is (closer to -1000 HU) the more quality the reconstruction method is. Airways segmentation represents an inevitably preprocessing step, which is presented in Sec. 1.3.

Once the quality measurement of anatomical structures reconstruction is established, mutual comparison among considered reconstruction methods can be performed. Comparison of data reconstructed by diverse methods from a single set of projections is not problematic as they are perfectly aligned and identical airways segmentation mask is used. Problem arises when the reconstructions of 80% and 20% dose scans have to be compared. Both scans are naturally displaced due to respiratory movements. Moreover, thanks to rapidly increased noise level in a 20% scan, some airways branches, which are correctly segmented in S_{80}, may remain unsegmented in S_{20}. Different voxels, thus, may enter quality measurement and comparison among reconstructions method would be inconsistent. Reliable methods for CT image registration are, of course, available, however, interpolation necessary for geometric transforms would negatively influence the quality measurements. A method which unifies both airways segmentations and allows for comparison of corresponding airways voxels in both scans is presented in Sec. 3.1. Image registration is, in this method, used in such way that none image data are affected by interpolation.

Very interesting results may be obtained when quality of airways reconstruction is related to airways thickness. Ability of considered reconstruction methods to properly reconstruct details with different sizes may be revealed. A method which would be able to assign local thickness to each voxel of segmented airways is needed and is presented in Sec. 3.2.

Besides objective fully automatic evaluation of quality of airways reconstruction, a subjective medical quality evaluation was also performed. Four experienced radiologists independently evaluated and rated image quality of individual reconstruction methods in terms of four "technical" image quality parameters (image noise, image artifacts, anatomical details, sharpness) and four parameters related to medical diagnostic process (low-contrast resolution, total impression of the reconstructed image, possibility of influencing the description, and possibility of influencing the examination's conclusion). Only the "technical" image quality parameters are evaluated in this thesis. A methodology for statistical evaluation of subjective medical image quality assessments is presented in Sec. 3.3 and resulting findings are summarized in Sec. 4.

Objective assessment of quality of airways reconstruction can be considered as measurement of ability of imaging system to properly reconstruct image details. In order to validate the proposed objective method, it can be compared with subjective medical evaluation of a details parameter. The results of this comparison are summarized in Sec. 4.

3.1 Determination of corresponding voxes between segmentations of 80% and 20% dose scans

A proposed method for correction of inconsistencies between airways segmentation of 20% (S_{20}) and 80% (S_{80}) dose scans uses two fully automatic registration steps. Image registration is the technique frequently used in medical image processing. It targets to finding a best possible spatial relationships between two images. Among a number of published registration methods a group of methods utilizing optimization of intensity based cost functions are the most suitable for the given registration problem.

The proposed correction can be divided into four main steps as follows:

1. Flexible registration of data from single medical examination acquired with 80 % and 20% dose yielding parameter vector $\hat{\boldsymbol{\mu}}$ of geometric transform $\boldsymbol{T}_{\hat{\boldsymbol{\mu}}}$ such that transformed 20% scan is optimally (in a sense of used similarity measure) spatially identified with 80% scan.

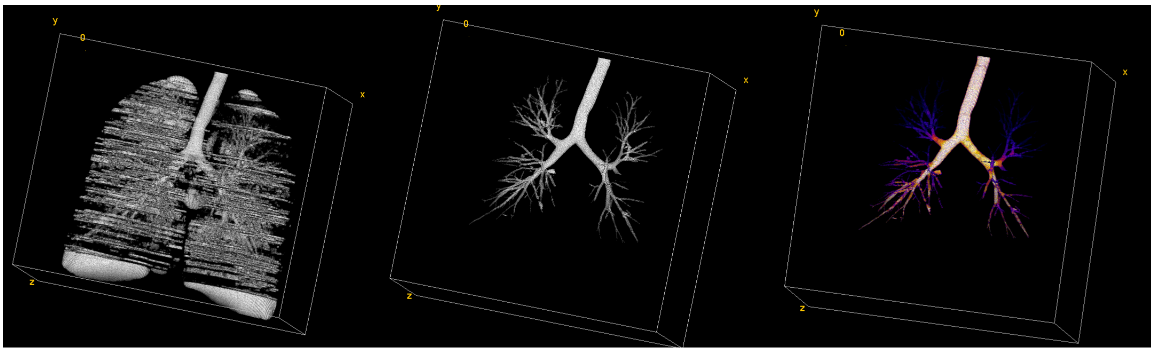
2. An airways segmentation of 20% scan, obtained by an approach described in Sec. 1.3, is geometrically transformed by $\boldsymbol{T}_{\hat{\boldsymbol{\mu}}}$.
3. A voxel by voxel intersection of S_{80} and $\boldsymbol{T}_{\hat{\boldsymbol{\mu}}}(S_{20})$ according to

$$S_{20\cap 80} = S_{80} \cap \boldsymbol{T}_{\hat{\boldsymbol{\mu}}}(S_{20}) \tag{3.1}$$

is computed, hence, only voxels located on identical spatial coordinates which are active in both airways segmenations are preserved.
4. Another flexible registration is used to calculate inverse geometrical transform $\boldsymbol{T}_{\hat{\boldsymbol{\mu}}}^{-1}$ which cancels $\boldsymbol{T}_{\hat{\boldsymbol{\mu}}}$ and $S_{20\cap 80}$ is transformed to be spatially consistent with S_{20}.

Both registration steps are performed using a publicly available registration package Elastix described in [9] which is often used for registration of a medical image data.

3.2 Measurement of airways thicknesses



(a) (b) (c)

Obr. 3.1: Visualizations of stages of airways segmentation and local thickness measurement by volume rendering: (a) airways candidates produced by a graph-cut segmentation of data enhanced by gray-scale morphological reconstruction, (b) final airways segmentation after 3D region growing, (c) visualization of airways local thickness map.

Thanks to gradually decreasing thickness of individual airways tree branches as they are approaching peripheral lungs parts, ability of the considered reconstruction methods to faithfully reconstruct structures of different sizes (i.e. airways with different thickness) can be evaluated. Hence, a parametric map which assigns a value of airways local thickness to each voxel needs to be derived. A method for evaluation of local thicknesses in binary data based on medial axis transformation is used. Whole segmented airways tree is divided into three parts according to local thickness measured in millimeters (from 0 mm to 4 mm, from 4 mm to 8 mm and thicker than 8 mm) and objective image quality is evaluated separately in those parts.

3.3 Subjective Medical Image Quality Evaluation

Four experienced radiologists independently evaluated and rated four “technical” image quality parameters (i.e. parameters related to CT data acquisition process); image noise, image artifacts, anatomical details and sharpness. A modified 5-point Likert scale ranging from -5 points to +5 points were used. The value of image quality parameters of data reconstructed using FBP at a 80% dose always had a value of 0 points (FBP is reference reconstruction, other methods are, thus, evaluated relatively to quality of FBP). Statistical analysis requires a single value of the quality score for a given data reconstruction. Such value was obtained as the mean value calculated among the medical experts.

Many statistical tests (e.g. among patient groups, depending on the particular hypothesis formulation) must be conducted to confirm that the mutual relationships are statistically significant. Wilcoxon rank-sum test, which is suitable for testing a null hypothesis stating that two tested groups of subjective evaluations are samples from a distribution with equal medians against the alternative that they are not, is used. A positive test result indicates rejection of the null hypothesis at the 5% significance level and acceptance of the alternative hypothesis (medians of the tested groups are not equal). A negative result indicates failure to reject the null hypothesis at the 5% significance level (medians of the tested groups are equal). When the difference between group medians is statistically significant, then the medians are compared. Whether the subjective quality evaluation in a certain group is significantly lower or higher than in another group is thus determined and a hypothesis can be rejected or accepted.

Results of the proposed hypotheses testing are summarized in Sec. 4.

4 RESULTS

As already mentioned, $iDose^4$ method should not significantly change the spectral properties of noise in reconstructed data compared to FBP reconstruction. This statement was confirmed on the undertaken phantom study, see results in Tab. 2.2. However, thanks to the proposed methodology, 1D NPS, and thus the index of stability of noise frequency properties, can be evaluated in diverse tissues of real patient data. Results of the evaluation of noise frequency properties stability in the real patient data, calculated according to the methodology proposed in Sec. 2.2, are summarized in Tab. 4.1. Their comparison with the stability indexes measured on the imaged phantom (summarized in Tab. 2.2) can be done. It can be concluded that the results measured on the imaged phantom are comparable with those calculated from real patient data (with exception of bones whose densities are, however, far from densities of water, where nonlinear iterative methods may have different properties). The proposed methodology is, thus, validated by phantom measurements for soft, adipose and air filled tissues.

Tab. 4.1: Results of analysis of 1D NPS center of gravity stability evaluated according to Eq. 2.2 separately for diverse tissues and $iDose^4$ levels.

	Soft	Bones	Adipose	Air Filled
iDose 30	0.198 ± 0.056	0.519 ± 0.181	0.345 ± 0.198	0.326 ± 0.205
iDose 50	0.513 ± 0.152	0.525 ± 0.172	0.659 ± 0.215	0.536 ± 0.235

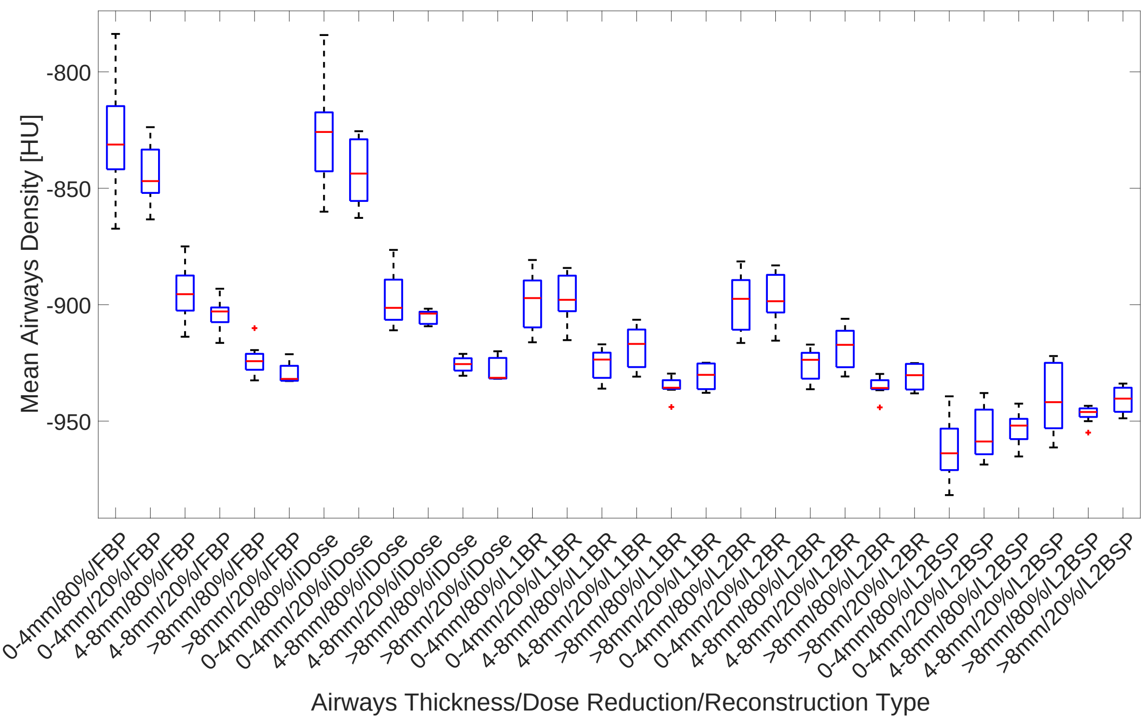
Based on the presented results, it can be concluded that the stability of noise frequency properties measured on phantoms is worse for higher $iDose^4$ level. The identical effect can be observed when the stability is computed from real patient data (with exception of bones where the difference between stabilities of the considered $iDose^4$ levels is very small). Stability of noise frequency properties of data reconstructed by $iDose^4$ with level 50 are much less dependent on a tissue type than of data reconstructed by $iDose^4$ with level 30. Frequency properties of noise inherent to soft tissue are least influenced by iterative reconstruction compared to classical FBP method (i.e. have the best stability of noise frequency properties).

Tab. 4.2: Results of analysis of 1D NPS centers of gravity evaluated according to Eq. 2.1 separately for diverse tissues.

	Bones	Air Filled Tissue	Adipose Tissue	Soft Tissue
iDose 30	0.578 ± 0.018	0.546 ± 0.017	0.519 ± 0.011	0.520 ± 0.022

Besides evaluation of the stability of noise frequency properties among iDose[4] levels, proposed method enables also comparison of noise frequency properties among separate basic tissues. CoG of tissue 1D NPS calculated according to Eq. 2.1 are, rather than the stability indexes, this time compared. The results of CoG measurement of 1D NPS in diverse tissues of residual noise data ID 30 are summarized in Tab. 4.2. Based on the presented results, it can be concluded that noise in bones is composed of higher frequency components than noise in the rest of tested tissues. Comparing spectral properties of noise typical for adipose and soft tissue, it can be concluded that there is not a significant difference. This fact can be explained by similar character (they have very similar densities in CT scans) of both tissues.

Results of "The IMR project", which was focused on measurement of CT image quality in terms of fidelity of anatomical structures reconstruction via evaluation of mean density in segmented airways are depicted in Fig. 4.1 in form of box plots. The box plots express distribution of mean density (calculated for whole considered data set) in differently thick airways parts, in data reconstructed by diverse methods and acquired with different level of dose reduction. Based on the presented results,

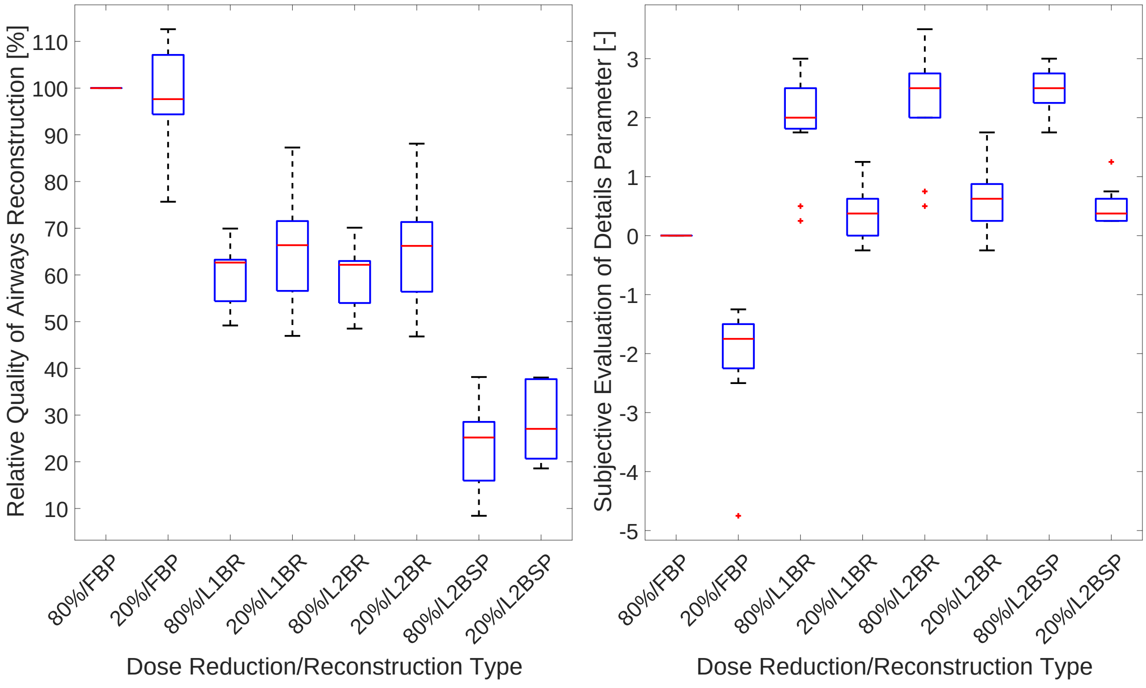


Obr. 4.1: Quality of differently reconstructed data evaluated via fidelity of airways tree reconstruction visualized in form of box plots. Each box plot express distribution of the image quality parameter for different airways thickness, reconstruction type and dose reduction.

several interesting conclusion are made. The qualities of anatomical structures reconstruction are nearly identical in data reconstructed by FBP and iDose^4 method for each airways thickness and level of dose reduction. This result is consistent with initial assumption that iDose^4 is pure statistical method which improves level of image noise (compared to the data reconstructed by FBP) and do not influence visualization of anatomical structures. On the other hand, model based iterative reconstruction types (labeled as L1BR, L2BR and L2BR) show significant increase of airways reconstruction quality (up to 130 HU lower mean density in L2BSP reconstructed data compared with by FBP reconstructed data). Those results support the initial assumption stating that model based iterative reconstruction positively influences fidelity of anatomical structures reconstruction. As data with different level of dose reduction are available, influence of applied dose can also be evaluated. No dramatic changes in fidelity of airways reconstruction can be observed, after reduction of applied dose from 80% to 20%. Considering FBP and iDose^4 reconstructions there is a slight improvement of image quality and, on the contrary, a slight decrease can be observed in data reconstructed by IMR. Analysis of airways based image quality measurements in dependence of airways thickness gives also very interesting results. Mean airways density increases (image quality decreases) with decreasing airways thickness for FBP, iDose^4 and also (though not so rapidly) for L1BR and L2BR reconstructions. Those reconstruction types are, hence, unable to maintain quality of reconstruction of small objects compared to larger ones. On the contrary, this trend is opposite in data reconstructed by L2BSP which provides data where quality of thin airways is even better than quality of the thicker ones. An interesting result is also that model based reconstruction types L1BR and L2BR provide for airways with large thickness (larger than 8 mm) similar quality data as FBP and iDose^4 but quality of those reconstructions (compared to FBP and iDose^4) rapidly increase in thinner branches.

A novel measure of image quality of anatomical structures reconstruction in terms of fidelity of airways reconstruction is presented in Sec. 3. As a subjective medical image quality evaluation of details in identical data set is also available, those two measures can be compared. The comparison may reveal whether the proposed objective image quality assessment (quality of the thinner airways are used to simulate evaluation of fine details) have potential to become a fully automatic method for evaluation of quality of anatomical details reconstruction in CT data.

In or order to be consistent with the objective medical image quality evaluation (described in Sec. 3.3) where quality of iteratively reconstructed data were assessed relatively compared to quality of by FBP reconstructed data acquired with 80% dose, objective evaluations are accordingly recalculated. Mean value of HU inside airways is recalculated as a percentage, taking the mean of HU inside airways in



Obr. 4.2: Subjective and objective image quality measurements in form of box plots. Each box plot express distribution of image quality for different reconstruction of data acquired with diverse dose reduction: (a) Objective measurements of mean density of airways parts thinner than 4 mm expressed relatively with respect to quality of data acquired with 80% dose and reconstructed by FBP, (b) subjective medical evaluations of Details parameter.

by FBP reconstructed data with a 80% dose as 100% of image quality. Hence, e.g. 50% of quality of airways reconstruction means that mean value of HU in airways is about 50% lower than in by FBP reconstructed data acquired with 80% dose.

Both compared quality measurements are visualized in form of box plots in Fig. 4.2. It is evident that objective and subjective quality measurements agree in the following facts. Increase of image quality in iteratively reconstructed data acquired with 80% dose is evident in both evaluations. Subjective evaluations of data acquired with 20% dose shows decrease of image quality (compared to correspondingly reconstructed 80% scans) as well as the objective ones (though not so dramatic). On the other hand, results of the subjective evaluations show no significant changes in image quality among different types of IMR reconstruction method (L1BR, L2BR, L2BSP), however, according to the objective evaluation, L2BSP reconstruction type provides much better image quality than the other two types.

5 DISCUSSION

The methodology for estimation of noise characteristics from real patient data are established in the first part of this thesis. Though it was shown that it provides, for computations of stability of noise frequency properties, similar results as on the phantom data (the method, thus, may be considered as validated by phantom measurements), there are some issues, which have to be discussed. Firstly the proposed extraction method were not validated for bones, which may be caused by greatly different densities of bones and water in in homogeneous phantom. Nonlinear object dependent iterative method may have different properties for densities of bones than for densities of water. This does not mean that the proposed method for tissue noise power spectrum estimation does not work well for bones, for its proper validation a phantom with homogeneous material which simulates densities of bones would be needed.

Secondly, for adipose and air filled tissues, segmentation introduced errors are too high to declare tissue noise power spectrum estimation reliable for purposes of measurement of noise frequency properties stability in data reconstructed by iDose^4. It is supposed that low spatial extent of those tissue types is the limiting factor.

Also subtraction of differently reconstructed data is necessary which moreover must have noise power spectra with similar shape (otherwise an error caused by the subtraction, described in Sec. 2.2 would increase), which is an evident limiting factor for general utilization of the proposed method. However, it have a great potential in estimation of tissue noise power spectrum from data acquired by dual energy scanners. As dual energy scanners provide couple of simultaneously scanned data with different noise realizations, anatomical structures may be, potentially, better suppressed by their subtraction and no errors caused by subtraction should occur.

Proposed detection of areas of radiological noise, which is very sensitive to setting of parameters of graph-cut based segmentation, may be considered another limiting factor. The parameters are constant for a given data set, but they need to be tuned after e.g. change of character of residual noise images to FBP minus ID30. **??** shows that detection of areas of dominant radiological noise largely increases rotational symmetry of estimated 2D tissue noise power spectra, however perfect rotational symmetry is still not achieved. Better rotational symmetry would be achieved by tuning the parameters of the algorithm of detection of areas of dominant radiological noise. Detection of more gentle directional structures would, on the other hand produce the tissue segmentation masks with more complicated shape; this will lead to increased segmentation introduced error. A compromise parameters tuning, thus, have to be searched for each application.

An increasing trend of stability indexes (i.e. worse preservation of noise frequency properties) may be observed with increasing iDose^4 level. However this dependence should be confirmed on a wider range of iDose^4 levels, which unfortunately are not available.

A novel CT image quality parameter which evaluates quality of anatomical structures reconstruction via fidelity of airways reconstruction is proposed in the second part of this thesis. As stated in Sec. 4, results of measurement of this parameter on the set of real patient data are consistent with initial assumption about capabilities of the considered reconstruction methods as provided by the vendor. From this point of view, it can be concluded that the proposed parameter is a valuable measure of image quality in terms of fidelity of high contrast anatomical structures reconstruction.

However, some discrepancies were revealed between subjective medical evaluation of Details parameter and objective measurement of fidelity of airways reconstruction. The objective measurement shows a rapid increase of image quality of by IMR L2BSP data, which can not be observed in the objective evaluation. This effect may be explained by different understanding of details in CT data. Medical experts may focus their attention to gentle structures which have low contrast to surrounding tissues, but airways are mostly well visible structures with good contrast to surrounding lung parenchyma.

Another discrepancy is in qualities of 20% dose scans evaluations which are much lower in subjective than in objective assessments. The subjective evaluations were not blinded which may cause that medical experts may intuitively falsely assign lower points to 20% dose scans. Another explanation may be again that medical experts focus their attention to structures with lower contrast to surrounding tissues than the airways have.

6 CONCLUSIONS

This thesis deals with measurement of image quality of iteratively reconstructed CT data and its comparison with the quality of data reconstructed by so far routinely used filtered back projection method. Recently published studies undertaken on special phantoms revealed that iteratively reconstructed data have some special properties (e.g. object dependent noise properties). Hence, some image quality measurements so far used in analysis of CT data have to be revised. Design of novel CT image quality parameters which respect specifics of iteratively reconstructed data and are fully automatically computed directly from real patient data is the main objective of this thesis. This thesis is divided into two main parts, in which data reconstructed by diverse methods are analyzed and different novel image quality parameters are proposed.

A novel methodology for estimation of tissue noise power spectrum which complexly describes frequency properties of noise inherent to separate tissues is presented in the first part; this methodology represents the crucial contribution of this thesis. It was demonstrated that noise in iteratively reconstructed data is object dependent in real patient data, which is the fact so far known only from phantom data. Frequency shift of 1D NPS center of gravity in by iDose^4 method reconstructed data (compared to 1D NPS center of gravity of the data reconstructed by FBP) was also evaluated. It was shown that iDose^4 method almost perfectly maintains spectral properties (and also texture) of image noise in all considered tissue types.

An extensive data processing was necessary for estimation of tissue noise power spectrum such as fully data driven gantry tilt correction, segmentation of cranial base and determination of areas of dominant radiological noise in residual noise images. All proposed data processing approaches may be, generally, utilized in other applications. Another important contribution of this thesis is represented by the methodology for design of two-dimensional spatially adaptive windowing functions, which are useful in applications where two-dimensional Fourier transform have to be calculated from a spatially limited subset of image data with irregular shape (e.g. from segmented data).

An approach for evaluation of quality of anatomical structures reconstruction via fidelity of airways reconstruction is presented in the second part. Results of the quality of airways reconstruction measured on real patient data are consistent with initial assumptions about the tested iterative reconstruction methods as provided by the vendor. However, some discrepancies between the proposed objective image quality measurement and subjective medical evaluation of details in corresponding set of CT data were revealed. Hence, it can be considered a valuable measure of quality of reconstruction of high contrast anatomical structures such as airways.

The proposed parameter, fidelity of airways reconstruction, therefore, can not be considered a general measure of quality of details reconstruction in CT data. It was shown that IMR reconstruction method rapidly increase quality of thin airways reconstruction compared to FBP and iDose^4 methods.

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