ischemic stroke detection,
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ACUTE ISCHEMIC STROKE: ENHANCED DISPLAY OF HYPODENSE CHANGES IN CT EXAMS

The Planar CT exams were used to detect acute ischemic stroke by hypodense symptoms notification. Infarction perception improvement by adaptive window settings, data denoising and local contrast enhancement in image and multi-scale domain is proposed. The post-processing methods enhance the subtlest, often invisible signs of hypodensity. Thus improved detection efficiency of perceptual ischemic changes was investigated. Data processing became more effective by initial segmentation of brain tissue and extraction of regions susceptible to tissue density changes. The new method was experimentally verified. The sensitivity of stroke diagnosis increased up to 56% in comparison to 12% of standard CT scan preview.

1. INTRODUCTION

Computerized tomography (CT) is widely used and considered as the method of first choice for differentiating the stroke syndrome. Moreover, CT imaging of acute stroke pathology allows the early assessment of irreversible ischemic injury [12]. The recent advent of thrombolytic therapy for acute stroke treatment makes as early as possible detection of areas of hypoattenuating ischemic parenchyma exceedingly important [11,12]. But the earliest signs of infarction, such as loss of sulcal delineation, obscuration of the lentiform nucleus, loss of insular ribbon and/or hyperdense middle cerebral artery are quite subtle on CT or literally invisible. Afterwards, it becomes possible to detect a slight hypodense area of infarction either in the cortices or the basal ganglia [6,11,12,13].

The purpose of our study was to improve the ability to detect the changes of acute ischemic brain parenchyma on emergency CT scans. Enhanced visibility of any stroke symptoms, i.e. more distinguished or extracted subtle and hidden hypodense signs make diagnosis more effective. Suggested post-processing methods are based on data segmentation, wavelet-based denoising and local contrast enhancement. Advance studies with non-standard window width [9] and centre level settings or statistical comparison of corresponding regions of segmented hemispheres [1,5] were used as the initial rationales for the improvements.

1.1. DETECTION OF HYPODENSE AREAS

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Hypodense changes were found to be the most frequent sign of early ischemia. A decline in cerebral blood flow causes the brain tissue to immediately take up water. Thus in the early stage of cerebral ischemia tissue changes consist mainly of alteration in water and electrolyte content. A diverse 2-4% increase in brain tissue water within 4 h of MCA occlusion was noticed in several experiments [3,12]. Increase in water content causes the lowering of brain tissue attenuation: a discrepant decrease of about 1.3-2.6 HU for 1% change in water content [1,3,11].

To enhance contrast resolution for hypodense areas, the narrowed display window for CT scan review is used (in comparison to normal window range of 0-80HU). But at the same time the signal/noise ratio and interpretation clarity is reduced. Detecting slight density changes to compare the hemispheres while slowly changing the level may be misleading, especially for inexperienced viewers since any apparent changes are not related to the anatomical background. Nevertheless, the detection of acute ischemic brain parenchyma with nonenhanced CT scanning was facilitated by soft-copy visual review at a diagnostic workstation by using narrow window width [9]. Detection sensitivity was increased from 57% with standard window settings (centre level setting of 20HU and window-width of 80HU) to 71% with narrowed window (window centre of 28-36HU and width of 1-30HU), without loss of specificity.

1.2. STROKE EXTRACTION: MULTISCALE HYPODENSITY ENHANCEMENT

Many methods of local contrast enhancement to visualize hidden structures in medical images were used [8,14] but, as far as we know, not for early stroke detection. Adaptive histogram equalization use a local window for each individual pixel and compute the new intensity value based on the local histogram defined in the local window. Diagnosis based on a single CT image is the result, which is more convenient because there is no need to switch between different window settings for cross-examination purposes between different tissues and organs. Interpretation time is significantly lowered in comparison to diagnosis based on conventionally displayed images. However, shadow-like artefacts appeared in rather homogenous regions and fine structures were diluted for some cases.

Artefacts may be reduced in multi-scale data processing [2,4,7,10]. Post-processing in wavelet domain was less susceptible to local perturbations with beneficial noise suppression and selective contrast enhancement. Generally, wavelet-based analysis is excellent tool for useful signal enhancement. It offers additional capability of modelling and modifying useful information . over successive scales and subbands. A correlation of high frequency information across scales portrays even very weak edges and region distinctions [2,7].

2. MATERIALS AND METHODS

Two stroke visualization methods were proposed: adaptive window of enhanced contrast resolution and wavelet-based image processing method to enhance early stroke detection. Multiscale stroke display is based on grey-to-white tissue segmentation, noise suppression in higher frequency bands of detailed scales and nonlinear contrast enhancement over successive scales.

Histogram analysis managed adaptive window selection. Band-pass filtering between -5 to 70HU was used as initial window thresholding and ROI selection. Next, the window centre was estimated as the second maximum (from the lowest values) of the pixel occurrence frequency of the ROI. Adaptive window width for display was set to 20HU.

We proposed the conception of stroke display as a kind of intelligent data visualization method that communicates enhanced ischemic hypodensity signs to the observers, especially for ‘radiologically silent’ cases. It complements conventional CT display with additional display highly specific to infarct cases.

Multi-scale method with local contrast enhancement to increase the visibility of poorly circumscribed hypodense regions was applied. Image wavelet decomposition and nonlinear processing over scales and subbands were adjusted to suppress the noise and increase contrast resolution. Nonlinear reduction of small coefficients over scales followed by amplifying denoised coefficients in selected subbands was applied.

Initial segmentation of the regions susceptible to ischemic density changes was used to eliminate false diagnostic indications caused by enhancing unsuitable density distinctions. False positives have to be avoided since treating ineligible patients with intravenous thrombolysis is associated with an unacceptable risk of hemorrhage and death. Segmentation was based on suitable tissue window cut off. We assumed X-ray attenuation in cranial CT in a range of 35-45HU for gray matter and 20-30HU for white matter. Hypodensity of gray matter causes a diminished contrast to adjacent white matter and a loss of anatomical margins can be noticed more clearly because of increased contrast resolution. Thus segmentation window of width 30HU with center level setting of 35HU seems to be the most suitable for early stroke detection. Because of CT number variations, slight adaptive modification of such window was necessary.

The proposed the following algorithm of selected CT layers processing:

1. **Two stage segmentation of stroke compliant ROI**
   - the brain extraction to de-skull the brain in the image: band-pass filtering between -5-50HU is made to get rid of useless structures and the mean value of brain ROI (*meanroi*) is calculated;
   - selection of ischemic stroke tissue ROI: image window is adaptively adjusted so that grey and white matter can be easily distinguished; adaptive window is set to the range of [10,*meanroi*+10] HU to extract brain tissue of grey matter to white matter density and reject clear brain sulcus, old strokes and other structures useless in early stroke detection; all pixels out of stroke tissue ROI are set to *meanroi*.
2. **Wavelet-based denoising and contrast enhancement**; dyadic wavelet decomposition with 6 scales is applied; a biorthogonal filter bank with 5/3 taps of low pass filters for analysis and synthesis: g_0=[-1/8,2/8,6/8,2/8,-1/8] and h_0=[1/4,2/4,1/4] respectively are used and wavelet coefficients are modified as follows:
   - for noise reduction, coefficients magnitudes were decreased in middle and high frequency subbands according to power-law formula: $d = c \cdot |c|^p$, where *c* is the wavelet coefficient value normalized within the scale it belongs to, power p=0.7; the modified *d* value of the coefficient is next renormalized to *x*;
   - for contrast enhancement, each wavelet coefficient *x* at the successive scales is modified to $y(x)$ according to the following rules: $y(x) = x \cdot (m/n)^p$ for $|x| < n$ or $y(x) = x \cdot (m/|x|)^p$ for $n \le |x| < m$ or $y(x) = x$ for $|x| \ge m$, where p=0.9 determines the degree of nonlinearity in the rescaling of the coefficients, and the parameter *n*

corresponds to the noise level; n and m were adaptively calculated for each scale as follows: $n = \min_{x \in scale}\{|x|\} + 0.3\left(\max_{x \in scale}\{|x|\} - \min_{x \in scale}\{|x|\}\right)$ and $m = \min_{x \in scale}\{|x|\} + 0.9\left(\max_{x \in scale}\{|x|\} - \min_{x \in scale}\{|x|\}\right)$.

3. **Processed data visualization (stroke display);** perception conditions are set to increase visibility of tissue density distinction. Extracted and enhanced stroke ROI is rescaled to a limited brightness range of 0-255 with contrast enhancement by histogram equalization. Other useless soft brain tissue is set to 255 in order to increase contrast perception for hypodense areas. Non-brain tissue is reconstructed according to a conventional bone window of source image. □

To verify proposed method, a set of 11 test CT exams of brain including clinically confirmed cases of stroke appearance, which contained a variety of ischemic abnormalities, was shown to two experienced radiologists from different medical centres. Conventional window display settings and next additional display: adaptive stroke window review or wavelet-based processed images as stroke display were used. We tested radiologists' ability to find infarcted areas in a blinded reading of plain CT images with and without the aid of the enhanced hypodensity display.

The exams of 8 patients aged 42–85 years (mean 69 years) with an acute MCA territory and pons infarct were used. Mostly cases really difficult to detect stroke (i.e. ‘silent’ cases of acute stroke) were selected. The time between the onset of symptoms and the early CT examination ranges from 1 to 5 hours (mean 2.7 hours). Follow-up CT (from 1 to 10 days after the ictus) was used to determine the location and size of the infarct. Additionally exams of 3 patients with a normal CT as a control group were used. The CT scans of all patients were analyzed by observers, unaware of the history. They first assessed source CT images without any stroke-oriented post-processing. They selected viewing parameters (window and the center) according to their stroke experience and own suggestions. Next additional enhanced image displays were shown to verify, change or assure initial assessment for the presence and site of any infarction. In any case of formulated diagnosis the observer was asked to assess whether additional stroke view provided a more certain diagnosis. Scale from 0 to 3 (where 0 means clear stroke absence and 3 - sure presence) was used to graduate the certainty of diagnosis.

3. RESULTS AND CONCLUSIONS

The examples of using enhanced brain displays with improved perception of hypodensity are presented in fig. 1. The sensitivities of acute stroke detection, mean numbers of false positives and assigned accuracy numbers of the diagnosis based on unenhanced CT were obtained (table 1). Conventional CT scan review was compared to use of additional enhanced image review with adaptively determined window or with additional post-processing in wavelet domain.

Reported results indicate that stroke-oriented enhancement based on adaptive window settings and image processing in wavelet domain may facilitate the interpretation of CT scans in acute infarction. Using stroke display improved the diagnosis of early infarcts in 100% (8/8) of test cases (and in 62% (5/8) of test cases by applying adaptive window). With enhanced stroke display 56.3% (9/16) of infarcts were correctly detected compared to 12.5%(2/16) indications based only on conventional image review. Detection sensitivity was also increased for adaptive window method, and was equal to 31% (5/16). All normal CT studies were correctly identified with stroke-oriented view and without it. However, one false positive diagnosis for acute infarct exam (wrong site) without the aid of additional display was noticed. It was corrected with a help of enhanced displays. There was no case in which a correct diagnosis made without stroke enhancement was falsely revised.

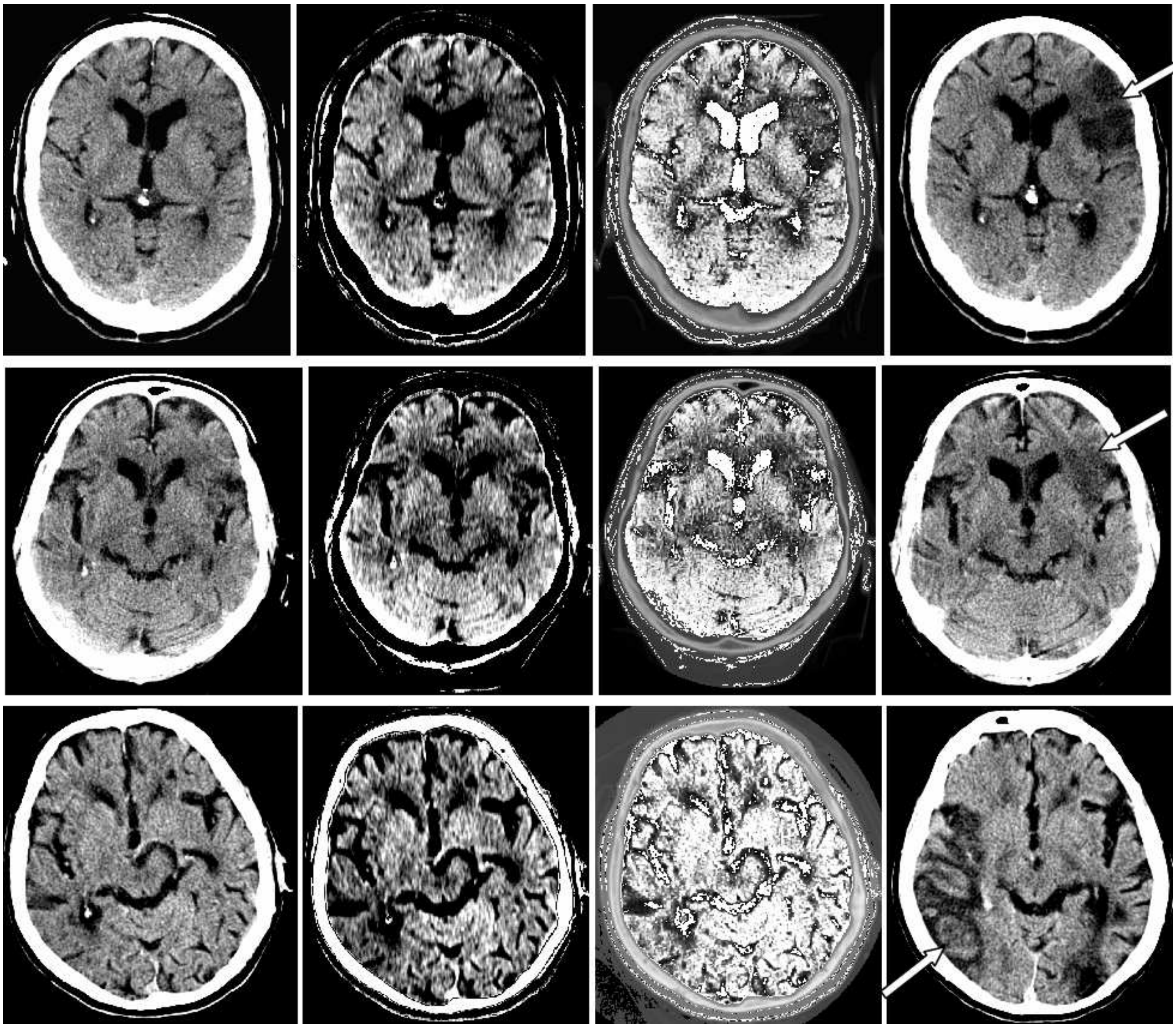

Fig.1 Three selected examples (in successive rows) of improved acute stroke detection: early stage of infarction in 40/30 window (left column), histogram-based window adjustment (middle-left), wavelet-based image processing (middle right), and follow-up CT scans used for confirmation (right column with infarctions indicated with arrows).

Tab. 1 Effectiveness of acute ischemic stroke detection; a sum of suitable scores with 0-3 scale gives sensitivity and false positive numbers.

Reader	**Exam visualization**	**Sensitivity**	**False positives**	**Sensitivity number (for infarction cases)**	**False positive number (for all cases)**
Expert 1	Standard	1/8	1/11	4	2
	Adaptive window	2/8	0/11	8	0
	Stroke display	5/8	0/11	14	1
Expert 2	Standard	1/8	0/11	4	0
	Adaptive window	3/8	0/11	9	0

	Stroke display	4/8	0/11	13	1
Total	Standard	2/16	1/22	8	2
	Adaptive window	5/16	0/22	17	0
	Stroke display	9/16	0/22	27	2

An improvement of acute stroke detection was noticed. The experimental results and provoked discussion of the experts confirmed primarily the usefulness of wavelet-based image post-processing methods. However, adaptive center level settings gave observable sensitivity and specificity improvement over the conventional scan review at least in several test cases. Reliable automatic window setting and diagnostic interpretation based on fixed CT image is more convenient and it can considerably accelerate the diagnosis of acute ischemic stroke with increased sensitivity and minimized possibility of false positives. According to the opinion of the radiologists stroke display would be particularly useful when enhanced images are displayed together with unprocessed scan preview, not instead of (as standalone). Intensification of density distinctions due to significantly increased local contrast resolution should be interpreted and utilized as a supplement to conventional display with window width and centre level settings done by observes according to their preferences.

The proposed stroke display method may be considered more generally as a conception of combined adaptive data windowing, wavelet-based image post-processing and histogram equalization in selected regions that is useful for acute stroke diagnosis. The detailed realization should be fatherly discussed, optimized and verified in clinical tests. Multiscale stroke data selection and classification according to semantic features seem to be crucial for improvement of stroke display effectiveness. However, additional more exhaustive clinical tests are necessary to suggest recommendation of the enhanced display methods as a replacement for conventional window display in acute ischemic stroke diagnosis.

BIBLIOGRAPHY

[1] BENDSZUS M., URBACH H., *et al.*: Improved CT diagnosis of acute middle cerebral artery territory infarcts with density-difference analysis, Neuroradiology, Vol. 39, pp.127–131, 1997.

[2] BONNIER N., SIMONCELLI E., Locally adaptive multiscale contrast optimization. Proc IEEE ICIP. Vol. 2, pp.1001–004, 2005.

[3] DZIALOWSKI A., WEBER J., *et al.*, Brain tissue water uptake after middle cerebral artery occlusion assessed with CT, J Neuroimaging, Vol. 14, pp.42–48, 2004.

[4] FAYAD L., JIN Y., *et al.*: Chest CT window settings with multiscale adaptive histogram equalization: pilot study, Radiology, Vol. 223, pp.845–852, 2002.

[5] GRIMM C., HOCHMUTH A., HUPPERTZ H., Voxel-based CT analysis for improved detection of early CT signs in cerebral infarction. /Eur Radiol/. B315-B315 (ECR - European Congress of Radiology), 2005.

[6] HACKE W., KASTE M., FIESCHI C., *et al.*, Randomised double-blind placebo-controlled trial of thrombolytic therapy with intravenous alteplase in acute ischaemic stroke (ECASS II), Lancet, Vol. 352, pp. 1245–1251, 1998.

[7] HAMMOND D., SIMONCELLI E., Nonlinear image representation via local multiscale orientation. Courant Institute. Technical Report TR2005–875, 2005.

[8] KIM J., KIM L., HWANG S., An advanced contrast enhancement using partially overlapped sub-block histogram equalization, IEEE Tran Circ \& Syst video technol., Vol. 11, pp.475–484, 2001.

[9] LEV M., FARKAS J., *et al.*, Acute stroke: improved nonenhanced CT detection - benefits of soft-copy interpretation by using variable window width and center level settings, Radiology, Vol. 213, pp.150–155, 1999.

[10] STARCK J., MURTAGH F., CANDES E., DONOHO D., Gray and color image contrast enhancement by the curvelet transform, IEEE Trans Image Proc., Vol. 12, pp.706–717, 2003.

[11] TOMURA N., UEMURA K., *et al.*, Early CT finding in cerebral infarction, Radiology, Vol.168, pp.463–467, 1988.

[12] VON KUMMER R., ALLEN K., *et al.*, Acute stroke: usefulness of early CT findings before thrombolytic therapy, Radiology, Vol. 205, pp. 327–333, 1997.
[13] WARDLAW J., MIELKE O., Early signs of brain infarction at CT: observer reliability and outcome after thrombolytic treatment—systematic review, Radiology, Vol. 235, pp.444–453, 2005.
[14] YU Z., BAJAJ C., A fast and adaptive method for image contrast enhancement. Proc IEEE ICIP. Vol. 2, pp.1001–1004, 2004.