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Evaluation of intracranial aneurysm coil embolization in phantoms and patients using a high-resolution Microangiographic Fluoroscope (MAF)

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Abstract

Intracranial aneurysm (IA) embolization using Guglielmi Detachable Coils (GDC) under x-ray fluoroscopic guidance is one of the most important neuro-vascular interventions. Coil deposition accuracy is key and could benefit substantially from higher resolution imagers such as the microangiographic fluoroscope (MAF). The effect of MAF guidance improvement over the use of standard Flat Panels (FP) is challenging to assess for such a complex procedure. We propose and investigate a new metric, inter-frame cross-correlation sensitivity (CCS), to compare detector performance for such procedures. Pixel (P) and histogram (H) CCS's were calculated as one minus the cross-correlation coefficients between pixel values and histograms for the region of interest at successive procedure steps. IA treatment using GDC's was simulated using an anthropomorphic head phantom which includes an aneurysm. GDC's were deposited in steps of 3 cm and the procedure was imaged with a FP and the MAF. To measure sensitivity to detect progress of the procedure by change in images of successive steps, an ROI was selected over the aneurysm location and pixel-value and histogram changes were calculated after each step. For the FP, after 4 steps, the H and P CCSs between successive steps were practically zero, indicating that there were no significant changes in the observed images. For the MAF, H and P CCSs were greater than zero even after 10 steps (30 cm GDC), indicating observable changes. Further, the proposed quantification method was applied for evaluation of seven patients imaged using the MAF, yielding similar results (H and P CCSs greater than zero after the last GDC deposition). The proposed metric indicates that the MAF can offer better guidance during such procedures.

Keywords

Intracranial aneurysms; microangiographic fluoroscope; MAF; coil embolization; cross-correlation sensitivity

1. INTRODUCTION

An intracranial aneurysm (IA) is a cerebrovascular disorder characterized by a localized dilation or ballooning of the blood vessel. IA's may result from congenital defects, preexisting conditions such as high blood pressure and atherosclerosis, or head trauma. They also occur more commonly in adults, but may occur at any age. About 6% of the population harbors such intracranial aneurysms, as indicated by autopsy and angiographic studies¹.

Subarachnoid hemorrhage (SAH), due to the rupture of an intracranial aneurysm, is a serious disorder with a high mortality and morbidity. It accounts for about one-quarter of cerebrovascular deaths and, despite improvements in the management of patients with SAH², most patients die as a result of the initial bleed or its immediate complications³. Intracranial aneurysm (IA) subarachnoid hemorrhage mortality occurs at a young age, producing a large burden of premature mortality which is comparable with ischemic stroke.^{4, 5} The median age of death from subarachnoid hemorrhage is 59 years compared with 73 years for intracerebral hemorrhage and 81 years for ischemic stroke⁵. Of the survivors, about 50% are left disabled and dependent on others in activities of daily living⁶.

Aneurysm treatment aims primarily at bleeding stoppage if SAH already occurred, reduction of likelihood of SAH, and ultimately, malformation healing and exclusion from the circulation. Currently two approaches are used: aneurysm neck clipping and endovascular embolization using detachable coils. In general, aneurysms that are completely clipped surgically do not return. However, the down side is that this approach is an extremely invasive procedure where under anesthesia, a section of the skull is removed, then the aneurysm is located visually and treated by placing a platinum clip across the aneurysm neck. In the endovascular approach, the neurosurgeon (interventionalist) inserts a hollow catheter into a femoral artery and threads it, using fluoroscopy guidance, through the body to the site of the aneurysm. Detachable coils (spirals of platinum wire) are passed through the catheter and released into the aneurysm. The coils fill the aneurysm, isolate it from the circulation, and cause the blood within to clot, which effectively eliminates the aneurysm from blood circulation. Sometimes aneurysm regrowth occurs and the procedure may need to be performed more than once during the person's lifetime.

The success of the treatment is related to the neurosurgeon's ability to fill adequately the aneurysm's dome and neck with minimal interaction with the aneurysm sack to prevent hemorrhage. Such procedures could benefit tremendously from high resolution guidance detectors over a small field of view⁷⁻²⁵. Such a detector is the micro-angiographic fluoroscope (MAF). The detector was used in clinical evaluations and its contribution has been appreciated by the neurosurgeons^{10, 26}. The clinical reports use qualitative assessments and treatment outcomes to describe the effect of the detectors on the interventional procedure which is acceptable in clinical reporting. However, a quantitative report on the MAF is challenging given the complexity of the procedure. Another limiting factor in preventing direct detector clinical comparisons is the unavailability of identical snapshots of the procedure since the MAF and the frontal detectors cannot be used precisely at the same time.

The goal of this paper is to develop quantitative metrics to compare aneurysm coiling imaged with two detectors: standard flat panel (FP) and MAF detectors in a controlled experiment with conditions similar to the clinical situation.

2. MATERIALS AND METHODS

Microangiographic Fluoroscope (MAF) system

A new x-ray, ultra high-resolution, Micro-Angiographic Fluoroscope (MAF) detector was incorporated into a standard angiographic C-Arm system. This detector consists of a 300 μm CsI input phosphor coupled to a dual stage GEN2 micro-channel plate light image intensifier (LII), followed by minifying fiber-optic taper coupled to a CCD chip. The detector has a round field of view with 3.5 cm diameter and 35 micron pixels. The LII has a large variable gain which allows usage of the detector at very low exposures characteristic of fluoroscopy while maintaining superior image quality (about 2 to 3 times the resolution of standard x-ray detectors). The detector is attached to the gantry using a specially designed holder onto the

AP C-arm of an x-ray biplane angiographic unit (Toshiba Medical Systems, Tustin CA) and is controlled by specially designed LabVIEW-based software designated CAPIDS¹² (Control, Acquisition, Processing, and Image Display System). The MAF is intended to be used similar to a surgical microscope. Any time a delicate intervention requires high resolution, the detector is brought into the field of view.

Phantom Evaluation

An anthropomorphic head phantom was created using a skull bone structure used for educational purposes, two elastomer aneurysm phantoms, and a tissue equivalent compound used to simulate the brain material (Figure 1). The aneurysm phantoms, Figure 1 (a), were placed in the cranial cavity and the cranial cavity was filled with the soft tissue equivalent compound, Figure 1(b).

The material used is similar to modeling dough and was well-suited for the purpose of completely filling the inside of the skull where sharp boney projections might puncture an incomplete filling alternative such as a flexible water bag.

The head phantom was placed on a plastic holder surrounded by a soft padding and secured to avoid accidental motion and reduce vibrations. The aneurysm phantom was connected to a tubing circuit to facilitate contrast injection through the phantom for road map simulation as well as to simulate the endovascular procedure. A 6 Fr Envoy straight guiding catheter (Boston Scientific, Natick, MA) was advanced to approximately 5 cm from the aneurysm neck. The aneurysm phantom was filled with a 50% saline/iodine contrast media to acquire the mask for roadmap simulation. Next, the contrast media was flushed with saline and a 2.2 Fr micro-catheter was advanced into the aneurysm dome through the guiding catheter.

Under fluoroscopic guidance, the aneurysms were embolized using Guglielmi Detachable Coils (GDC) fed through the micro-catheter. A FP and the MAF were used for the x-ray guided procedures. The GDC deposition was done using the MAF in multiple steps, whereby in each step 3 cm of the GDC was deposited into the aneurysm dome. The positions of the coils were imaged with both detectors: FP and MAF. Thus each view (filling instance) used for calculations, was identical for the two detectors. Once 3 cm of the coil was deposited a picture was taken with the MAF then with the FP. A 30 cm GDC was used; hence there were 10 different aneurysm filling instances.

Image quantification for comparison purposes during aneurysm coiling is a very challenging task due to both moving objects and new structure (coils) added to successive frames. To quantify changes in successive treatment instances observed with the two detectors we are proposing to use a new metric designated cross-correlation sensitivity (CCS) defined as one minus the cross correlation coefficient or the difference between cross-correlation and total correlation.

Cross correlation is one of the simplest but effective metrics to measure the similarity between two images that is invariant to linear brightness and contrast variations²⁷. We used the cross correlation coefficient to measure the dissimilarities between two instances of the treatment. A lower cross correlation coefficient was equivalent to the ability to observe or record bigger differences between the images of successive instances of the treatment.

We calculated two sensitivity parameters. The first parameter, which we refer as pixel CCS, describes the spatial differences and is defined as:

$$P_{k,k+1} = 1 - \frac{\sum_{i,j} (x_{i,j}^k - \bar{x}^k)(x_{i,j}^{k+1} - \bar{x}^{k+1})}{\sqrt{\sum_{i,j} (x_{i,j}^k - \bar{x}^k)^2 \sum_{i,j} (x_{i,j}^{k+1} - \bar{x}^{k+1})^2}} \quad (1)$$

where x is the pixel value, k refers to the image instance in a sequence, $\bar{x}$ is the average pixel in a given instance k and subscript i and j refers to the pixel location in a given image or ROI.

The second parameter, which we refer as the histogram CCS, describes the differences in the histogram of two images of the successive procedure instances and is defined as:

$$H_{k,k+1} = 1 - \frac{\sum_i (x_i^k - \bar{x}^k)(x_i^{k+1} - \bar{x}^{k+1})}{\sqrt{\sum_i (x_i^k - \bar{x}^k)^2 \sum_i (x_i^{k+1} - \bar{x}^{k+1})^2}} \quad (2)$$

where k refers to the image instance in a sequence, subscript i refers to the bin number in the histogram of value x in a given image or ROI and $\bar{x}$ is the average.

A region of interest was selected to overlap the aneurysm dome, and a histogram of gray-level values was derived for each of the instances. To quantify the observed changes, each image and the corresponding histogram was compared with the previous instance and the pixel cross correlation sensitivity parameter $P_{k,k+1}$ and the histogram sensitivity parameter $H_{k,k+1}$ were calculated. The CCS parameter takes values between 0 which indicates identical data distributions and 2 for anti-correlated data where 1 is no cross-correlation.

For the pixel CCS, the cross correlation coefficient could be much smaller due to the noise. To eliminate this issue we set a condition that the pixels with variances less than 1% be set back to the previous instance pixel value. We verified our condition by taking an ROI outside the aneurysm region where there is no change other than random noise and compared successive instances. For a 1% variation limitation, the pixel CCS of the background was ~ 0 verifying that there would be little contribution to the CCS from noise.

Patient Evaluation

The MAF was mounted on an x-ray image intensifier C-arm in the angiography suite. The MAF system was interfaced with the x-ray system and was used for various interventions including aneurysm embolization. Seven aneurysms were treated using MAF guidance. Since there was no means of quantifying the amount or timing of coils deposited during the procedure, we considered the entire run in which the coils were deposited and divided it into ten assumed equal intervals. The last image at each interval was considered as an instance, which was further used for CCS determination as described in the phantom experiment section. For three aneurysm treatments, the interventionalist was half way through the procedure before the MAF was used so we considered those cases as 50% coiled for the first interval and the remainder of the procedure was divided into five intervals.

RESULTS

In Figures 2, 3, 4, 5 we display two different treatments of aneurysm phantoms. In each figure we show five representative image instances with various amounts of the coil deposited. Below the image sequences we display the histograms, and the $P_{k,k+1}$'s and $H_{k,k+1}$'s between the displayed instances. In figures 2–3 display coiling of an aneurysm in the anterior circulation using direct fluoroscopy (unsubtracted), while Figures 4–5 we show

the coiling of a posterior circulation aneurysm using RoadMap (subtracted); however, both subtracted and unsubtracted images were available for both anterior and posterior aneurysm phantom sequences

In the histograms shown in Figures 2 to 5, the peaks corresponding to the coils emerge at lower gray values when compared to the initial instance. It can be seen that for the FP as soon as the first loops are deposited, the gray values are zero and any coils added on top will be added to the same histogram bin (gray value). However for the MAF the emerging peaks are much wider which translates into a better perception of the overlapping structures due to a larger MAF resolution and hence dynamic range.

It can be seen in the images that in the initial part of the treatment, when fewer than 50% of the coils have been deposited coil loops can be identified quite well with both detectors, as indicated by the non-zero CCS for both detectors shown in Figures 6 and 7. As the treatment continues the MAF becomes better than the FP in identifying newly added structures so that the CCS for the FP goes to zero indicating little visual change. Figures 6 and 7 show trends in the $P_{k, k+1}$'s and $H_{k, k+1}$'s as a function of the instance. In general the roadmap images of Figures 4 and 5 resulted in somewhat smaller correlation coefficients (larger CCS values) which indicate better ability to assess the differences between successive instances in the treatment. For the unsubtracted fluoroscopy (Figures 2 and 3), it can be seen for the FP, that the CCS curves (Figures 6 and 7) level after 50% of the coil deposition whereas for the MAF, there are still quantifiable differences until the coil is fully deployed.

For the clinical evaluation, seven patients have been treated using the MAF and the CCS values between successive instances are shown in Figure 8. Patients 1, 3 and 4 were already coiled 50% by the time MAF was used, while the rest were treated from start to finish using the MAF. CCS values (Figure 9) are somewhat greater than zero in all the cases although smaller as the procedure progresses. In addition there is a systematic oscillatory error which is due to the fact that the coil deposition speed is not constant between different instances.

4. DISCUSSIONS

The work presented here compares two detectors used for x-ray guidance during the coil embolization of intracranial aneurysms. First we focused on defining a quantifiable parameter to compare such complex procedures. While treatment outcome or subjective remarks are acceptable for clinical publications, a more quantitative metric may be helpful. We proposed a sensitivity parameter which is defined as one minus the image or histogram cross correlation coefficient, to report differences between successive instances of the treatment. Such a methodology is commonly used for other image processing tasks such as pattern matching, but to our knowledge it has not been used in medical imaging to assess the ability of a detector to differentiate between slightly different structures in an image sequence.

During phantom evaluation, the MAF and the FP had similar performances in the first part of the coil deposition (less than 50%). As more coils were added the FP histogram sensitivity parameter reached zero, indicating inability to observe overlapping structures. This could indicate a reduced dynamic range at low gray values of the detector itself and inability to distinguish coil detailed structure. The MAF on the other hand evidenced a histogram sensitivity parameter larger than zero at every point during the procedure, which translates into increased ability to observe overlapping structure even when the aneurysms were nearly filled.

The pixel CCS never reached zero during the experiments. This could be explained by the motion of the entire coil mass as more spirals of coil are being added. Except for the first

few instances, the MAF imaging resulted in higher values, which again is an indication of increased ability to assess smaller detail changes.

The clinical results followed a somewhat similar trend as the phantom experiment; the sensitivity parameters were high in the beginning of the procedures, indicating significant differences between successive instances. Once the aneurysms were partially filled, however, the values reached a limit larger than zero.

In summary, a new metric was used to evaluate the completeness of coil deposition into the aneurysm and to assess the benefit of using the MAF. The use of the cross-correlation sensitivity enabled accurate histogram comparisons and proved to be a good approach to track fine depositions of coils into the aneurysm dome. The results presented point towards a considerable improvement when using the MAF for treatment of the intracranial aneurysms, especially when there is a significant amount of coils already deposited. The ability to see such details may indicate the difference between a successful outcome and an inadequate result.

5. CONCLUSIONS

Data analysis shows that MAF is superior to the Flat Panel in multiple ways. First the neurosurgeon is able to better assess the dome filling from procedure beginning to end despite the highly attenuating platinum mass. The high resolution offers a better visualization of the pockets (un-filled regions). The new CCS metric used to compare the MAF with the standard FP detector demonstrated that the MAF may offer far better guidance during such intracranial aneurysm treatment procedures.

Acknowledgments

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Figure 1.
Experimental Setup: (a) bifurcation aneurysm phantom placed in the posterior circulation in a skull; (b) lower intracranial cavity filled with an organic compound similar to soft tissue; (c) data acquisition setup, the catheter is used to support a micro-catheter.

Figure 2.
Representative instances of the coil deposition during fluoroscopy in an anterior circulation aneurysm phantom using the flat panel imager shown with corresponding ROI histograms.

Figure 3. Representative instances of the coil deposition during fluoroscopy in an anterior circulation aneurysm phantom using the MAF, shown with corresponding ROI histograms.

Figure 4. Representative instances of the coil deposition during roadmap fluoroscopy in a posterior circulation aneurysm phantom using the flat panel imager, shown with corresponding ROI histograms.

Figure 5.

Representative instances of the coil deposition during roadmap fluoroscopy in a posterior circulation aneurysm phantom using the MAF, shown with corresponding histograms.

Figure 6. Image cross-correlation sensitivity plots for the phantom experiment evaluation, showing variation of the $R_{k, k+1}$'s for each image instance

Figure 7.
Histogram sensitivity plots for the phantom experiment evaluation, showing variation of the $H_{k, k+1}$'s for each image instance

Figure 8.
Instances of the aneurysms being coiled in various patients imaged with the MAF

Figure 9.
Sensitivity plots for the clinical data evaluation using the MAF