ORIGINAL CONTRIBUTION

Black Blood MR Angiography Using Three-Dimensional Fast Spin Echo (3DFSE) : A New Method for Intracranial MR Angiography

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Bright blood magnetic resonance angiography (MRA) methods ; (time-of-flight (TOF) and phase contrast (PC)), could fail in accurate depiction of turbulent, complex or slow flow within brain arteries. On the contrary, we demonstrated that black blood (BB) MRA is more effective to exploit the intracranial circulation of arteries, in such conditions. To create dark signal for black blood imaging, thin-section three-dimensional Fast Spin Echo (3DFSE) sequences with presaturation pulse below the imaged slab, were selected as the proper strategy.

In scan parameter optimization for this new method, the applied transaxial 3DFSE sequences with proximal presaturation pulse, first with fixed TR=1200ms and four different TE values (30, 68, 85 and 102ms), and then with fixed TE=68ms and four different TR cases (600, 1200, 1200 without presaturation and 1800ms), in four normal volunteers, resulted different sets of BB images for comparison with 3DTOF acquired with Slice-selective Off Resonance Sinc (SORS) method. Actual measurements of signal-to-noise ratio for internal carotid arteries (ICA) and middle cerebral arteries (MCA), cerebrospinal fluid (CSF) and white matter (WM) tissues, supported the flow/stationary background contrast assessment of the acquired images.

The results of BB MRA with presaturation in TR=1200ms and TE=68ms, satisfactorily indicated the better angiographic quality than those of without presaturation and TOF MRA. With minimum intensity projection (mip) for BB imaging and the above optimal parameters, particularly small vessel tracking could be accomplished better than the maximun intensity projection (MIP) for TOF imaging.

In the present study, BB MRA has been realized as a promising complementary to TOF MRA. The clinical application required a convenient post processing projection algorithm to prevent arteries overlapping with air existence area, possible calcified plaques, or to depict those arteries passing through the dark bone.

Keywords : MRA, black blood MRA, 3DFSE, intracranial circulation, brain vasculature imaging

Introduction

In magnetic resonance angiography (MRA) the precise extraction of the blood vessel structures from background tissues is the essential requirement. Therefore, this technique as a screening modality has to produce a signal with sufficient contrast and spatial resolution without artifacts. Time-of-Flight (TOF) MRA suffers from signal loss within the vessels, specially in complex flow due to turbulence-induced dephasing or saturation due to slow or recirculating flow[1)~3)]. On the other hand, black blood MR angiography which visualizes the flowing spins as significantly lower signal than surrounding tissues would be more effective, since the dephasing and saturation effects within the vessels in such conditions are advantageous for this application. Furthermore, the provided uniform dark signal by this method offers good vascular contrast not only in high flow vessels, but also in low velocity peripheral arteries[1),4)~7)], which are frequently encountered in diseased patients.

Although, as a method for brain vasculature imaging, three-dimensional (3D) thin slice scan is seriously needed for the precised delineation of the complicated vascular system, there has been few proper techniques reported for this purpose[4),5)].

Expecting the above described advantages of the method, we, as a preliminary study, tried black blood MR angiography by using 3D Fast Spin Echo (3DFSE) sequence[8)] and achieved several useful findings, which will be discussed in the following article.

Materials & Methods

The images were obtained in 4 normal volunteers (26, 32, 34 and 35 year-old) by using 1.5T (Toshiba 200 FX, Tokyo, Japan) and a quadrature head coil which was used to transmit and receive.

Transaxial three-dimensional Fast Spin Echo (3DFSE) sequence was appiled in combination with a presaturation pulse (SAT) added at 5cm below the imaged slab. Fig.1, shows the imaging slab accompanied with the proximal presaturation band and also antialiasing presaturation bands.

The image parameters for above black blood imaging were as ; FOV of 15cm, slice thickness of 1.6mm, number of partitions of 32, matrix size of 256×192 and signal averaging of 1. By using an interpolation along the slice direction, 57 slices of 0.8mm pitch were generated for evaluation. Because of the aliasing along the z-axis, we excluded 3 top slices and 4 bottom slices, making the total number of the 57 slices. 3DFSE with echo train length (ETL) of 15 and echo interval time of 17ms were used. The zero encoding line were written with 2nd, 4th, 5th and 6th echo for TEeff. value of 30, 68, 85 and 102ms, respectively. Finally, the image data sets were post processed by minimum intensity projection (mip) algorithm[4),9)].

In performing the TE optimization, by applying 3DFSE sequences in transaxial driection, first fixed TR=1200ms with SAT (SAT (+)) and four different TE values (30, 68, 85 and 102ms) were tried. According to the results, then for TR optimization, fixed TE=68ms and four different TR cases

Received July 10, 1995 ; reveised Nov. 27, 1995
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(600ms SAT (+), 1200ms SAT (−), 1200ms SAT (+) and 1800ms SAT (+)) were evaluated. Eight different sets of black blood images and one set of TOF images were obtained for the 4 subjects.

Signal intensities of gray matter (GM), white matter (WM), cerebrospinal fluid (CSF), bilateral internal carotid arteries (ICA) and bilateral middle cerebral arteries (MCA) were measured for each sequences with standard device of the MR system software. The averages and standard deviations of these measurements were used in computation of the signal to noise ratio (SNR) of above regions of interest. SNR was obtained by using $SNR = S/\sigma$, where S is the signal intensity and σ is standard deviation of the background noise measured in an image region representing air.

3DTOF MR angiography was obtained by applying the gradient echo pulse sequence with using the Slice-selective Off Resonance Sinc (SORS) method and TR (ms)/TE (ms)/FA (°) of 40/8/25. the imaged area, slice thickness, partition numbers and the inplane matrix were the same as the black blood sequences. The data set was processed by maximum intensity projection (MIP) algorithm[9)~11)].

Results

Considering the black contrast of blood flow signal in respect to the singnal of stationary background tissues in brain, the following results can be obtained from the related images shown in Fig.2-3, 5-6, and also from their SNR graphs shown in Fig.4, 7.

Figures 2-3, show the black blood images obtained with 3DFSE sequence in combination with proximal presaturation pulse, while TR was fixed to 1200ms, the shortest TE= 30ms showing dark CSF and bright white matter, was not optimal for vessel background context, (Fig.2a). Signal of CSF increased and that of WM decreased as TE

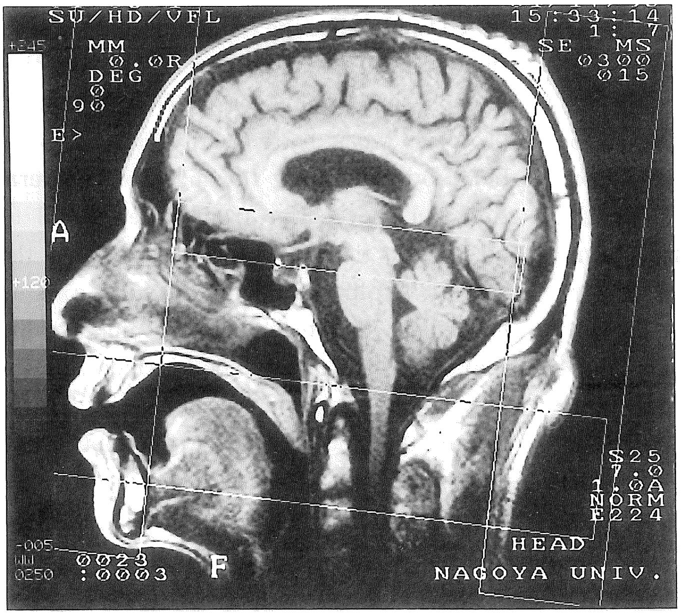


Fig.1. To create dark signal of blood flow, those regions in brain which the proximal presaturation pulse was applied for them are shown in this figure. A 8cm thick transaxial slab including the Wilis' ring was partitioned into the 32 slices of 1.6mm thickness. A 5cm thick presaturation (SAT(+)) slab was added proximal to the imaging slab with 3cm interval to ensure the out-flow effect. By using slice doubling technique, 57 slices with 0.8mm pitch were obtained.

incrementally increased, giving almost homogenous background signal around TE=68ms. Although, there observed a considerable amount of signal within ICA lumen when TE=30ms, flow void phenomena were observed when TE was equal or more than 68ms. Finally, in TE=68ms, while enough detectability for WM and CSF is observable, it was supposed to be optimal providing the best vessel to background contrast, (Fig.2-3, 4).

Figures 5-6, indicate the result of TR optimization. As TR increased, the white matter signal generally increased. Concerning the flow signal, TR=600ms and TR=1200ms SAT (−) revealed much signal within the ICA lumen, TR=1200ms SAT (+) and TR=1800ms SAT (+) satisfactorily suppressed the signal within the vessel the lumen. Although, TR=1800ms SAT (+) offered the best contrast, considering the total scan time, TR=1200ms SAT (+) were employed for practical choice, because the contrast is already acceptable, (Fig.5-6, 7). Accordingly, TR/TE 1200ms/68ms with proximal presaturation pulse selected for future use.

The post processing images related to minimum intensity projection (mip) for black blood MRAs and maximum intensity projection (MIP) for TOF MRAs are shown in Fig.8-10. In black blood MRA, particularly the small vessel tracking could be accomplished significantly better than the TOF MRA.

Discussion

Although, 3D TOF MR angiography has been used as an effective method for depicting noninvasively vascular structures, nonuniform signal loss within vessels is problematic, particularly for large 3D volume, short repetition time (TR), and distal slowly flowing spins. Spin phase dispersion and progressive saturation of inflowing spins into the three dimensional slab are the two main factors for unfavorable signal loss in these cases[1)~3)].

The peripheral arteries in the brain which are relatively small and tortuous, with turbulent or complex flow, are supposed to be particularly sensitive to spin saturation and dephasing. Furthermore, the presence of arteriosclerotic disease would cause such kind of complex or slow flow and may lead to poor MR angiographic visualization of the vessels. Therefore, the real understanding of the vessel structures would be impaired in such conditions[1)~3)].

3D phase contrast (PC) method is less sensitive to spin saturation and also gives better visualization for the slow flow and small vessels, however, this method is not suited to visualize the rapid flow and the slow flow at the same time and is also sensitive to dephasing[1)]. Thin-section 2D TOF imaging protocols work better with slowly flowing blood by minimizing flowing proton saturation, but they suffer from lower signal to noise ratio than 3D TOF methods and the spatial resolution along the slice axis is limited[12)]. Other techniques to minimize the spin saturation of the blood include ; use of intravenous gadolinium contrast material to shorten the blood T_1[13),14)], or the appropriate manipulation of acquisition parameters (i.e., longer TR, smaller flip angle, and reduction in slice thickness) could only be achieved, sacrifying the imaging time, contrast, cover-

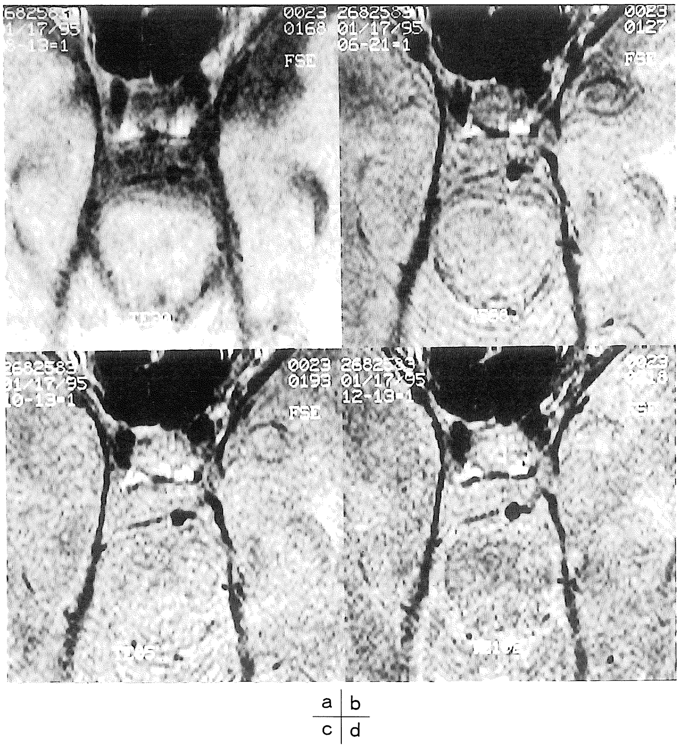


Fig.2. 3DFSE black blood images obtained with fixed TR=1200ms SAT(+), in four volunteers. (a) TE=30ms, WM tissue was appeared with higher signal intensity in respect to CSF, ICA and MCA. Hard differentiation between vessels and CSF. Considerable signal inside the ICA lumen was attributed to rapidly moving spin which passing across the presaturation slab and still remaining within the imaging slab, causing to form spin echo signal. (b) TE=68ms, as the optimum one provided enough contrast for WM and CSF, also uniform signal intensity for ICA and MCA vessels was observable. The continuity of MCA vessels was depicted clearly, while, that kind of imperfect out flow effect in (a) was vanished. In (c) TE=85ms and (d) TE=102ms, the signal intensity and the continuation of the vessels were not as well as those of the TE=68ms acquisition, also, the longer scan time matter was not favorable.

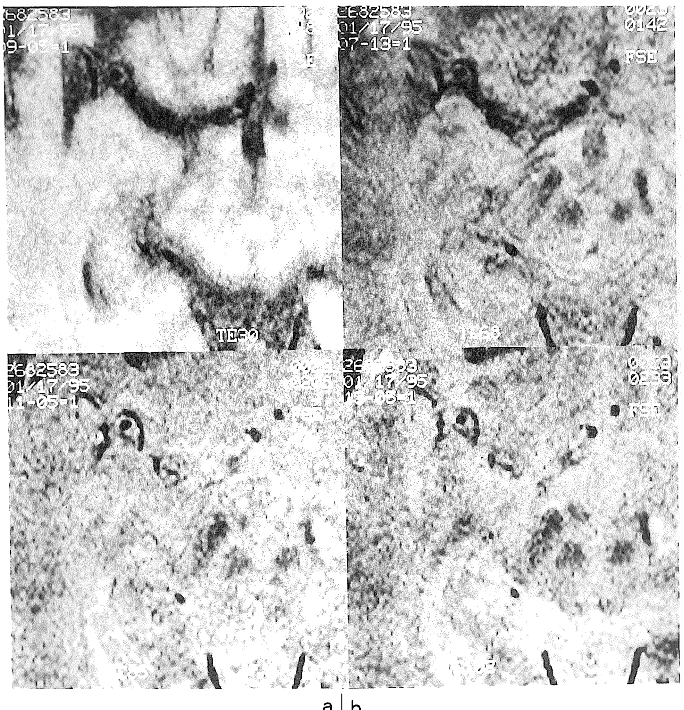


Fig.3. Same acquisition as Fig.2 (3DFSE black blood images with fixed TR=1200ms SAT(+), in four volunteers), MCA vessels detection is shown here with more details. (a) TE=30ms, (b) TE=68ms, (c) TE=85ms, (d) TE=102ms. Particularly, enough detectability for MCA vessels and stationary background tissues has been achieved in the image of TE=68ms in comparison to the other TEs.

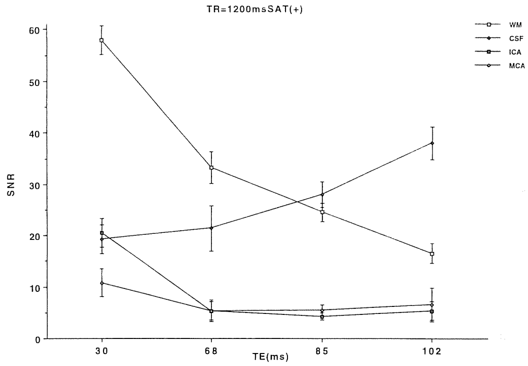


Fig.4. Signal-to-noise ratio (SNR) measurements for vessels and stationary background tissues in brain as a function of TE (3DFSE black blood MR angiography with fixed TR of 1200ms in combination with proximal presaturation pulse (1200ms SAT (+)), in four volunteers). In TE=68ms, the acquisition of the lowest and same SNR for ICA and MCA vessels, also enough higher SNR for WM and CSF, besides the less time-consuming requirement, all lead to select this TE value as the optimum one.

age or money[15),16)]. TONE (tilted optimized nonsaturating excitation) by applying spatially variable flip angle execution, is reported as an useful method in reducing the blood flow saturation without lengthening image time, but the variation in signal intensity of the background stationary tissues which is evident in MIP images could be a problem[17)]. Alternative methods such as multiple thin-slab 3D acquisitions have demonstrated the reduction in loss of the contrast to nois ratio (C/N) due to saturation effect, however, with the overlapping at the slab edges in MIP images and the lengthening the examination time, their efficienecy have been reduced[1),18)]. In MTS (magnetization transfer saturation) and FS (fat saturation) pulses, saturation of flowing spin can be avoided by applying spectral presaturation pulses to frequencies, away from that of flowing blood to reduce the

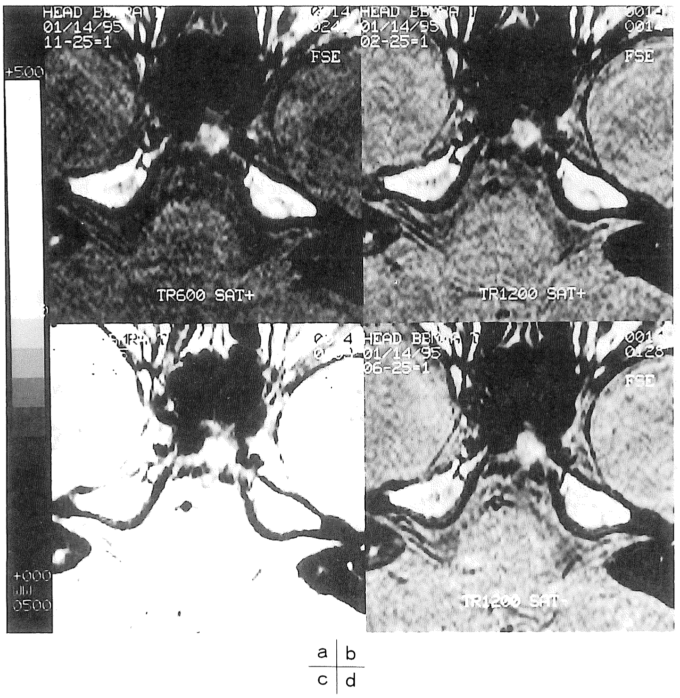
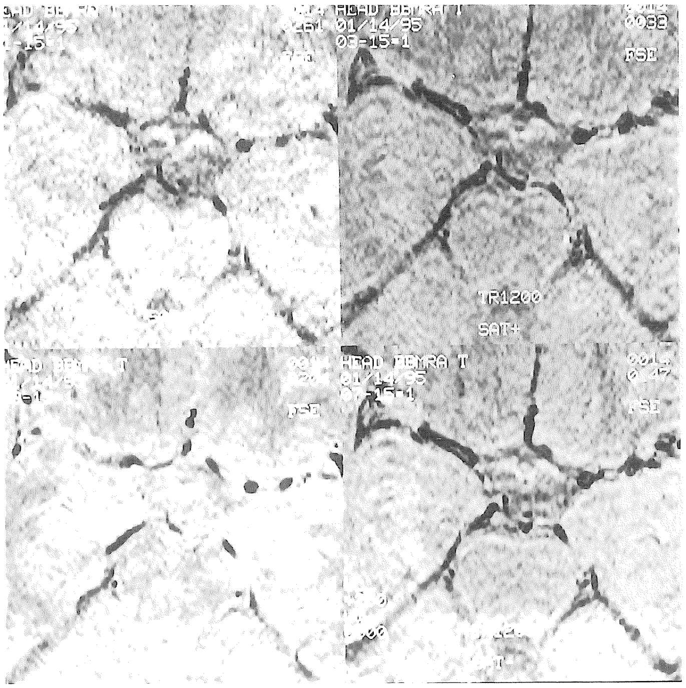


Fig.5. 3DFSE black blood images obtained with fixed TE=68ms, in four volunteers.
(a) TR=600ms SAT(+), high background noise caused the lowest contrast image for this shortest TR. (b) TR=1200ms SAT(+), better detectability for vessels and background tissues has been achieved in respect to the other TRs. (c) TR=1800ms SAT(+), WM and CSF have been appeared with the highest intensity, with hard differentiation between them. ICA and MCA vessels have been almost good detectability in such bright intensity. (d) TR=1200ms SAT(+), ICA and MCA vessels have been appeared non- uniformly, such that some bright intensities in the lumen of the vessels can be seen, clearly. Wash-out flow alone can be responsible for this matter. Considering better flow/background contrast and also the time consuming matter, TR=1200ms SAT (+) image can be selected as the most proper one among the other cases.



a | b
c | d

Fig.6. Same acquisition as Fig.5 (3DFSE black blood images obtained with fixed TE=68ms), showing the MCA vessels in more details. (a) TR=600ms SAT(+), (b) TR=1200ms SAT(+), (c) TR=1800ms SAT(+), (d) TR=1200ms SAT(−). MCA vessels have been exploited continuously in TR=1200ms SAT(+) image. In TR=1200SAT(−) image, the ICA vessels intensity has been decreased, and the flow void has been appeared in MCA vessels. Therefore, the uniform black blood signal of TR=1200ms SAT(+) assured the selection of this TR as the optimum one.

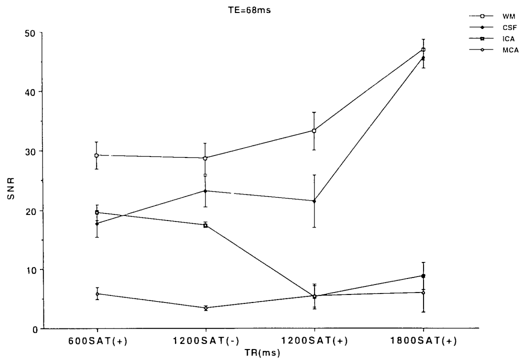
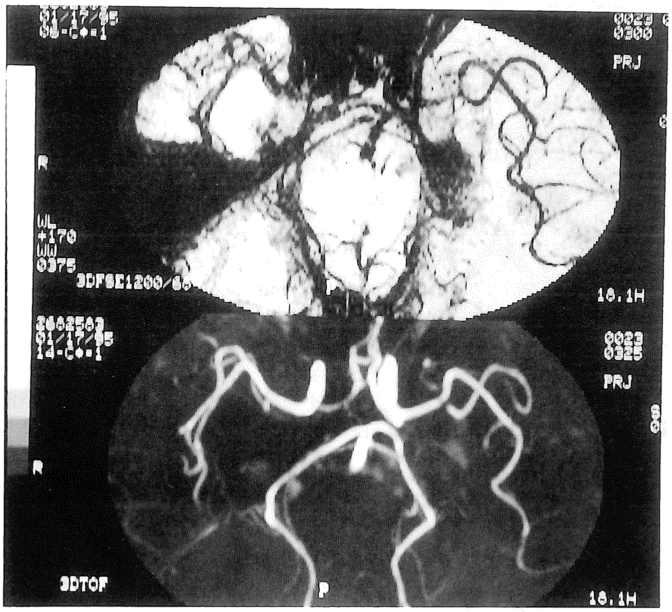


Fig.7. Signal-to-noise ratio (SNR) measurements for vessels and stationary background tissues in brain as a function of TR(3DFSE black blood MR angiography with fixed TE of 68ms, in four volunteers, SAT(+) and SAT(−) are represent for with and without proximal presaturation applications, respectively). SNRs in TR=1200ms SAT(+) show the proper values for providing the required dark flow/background contrast, as observed in related images, (figures 5-6). TR=1800ms SAT(+), as the other suggestion for optimum TR, needs more longer examination time, however, (12 minutes).

unwanted background signals, however, with increasing in specific absorption rate (SAR) and the minimum achievable TR[19),20)].

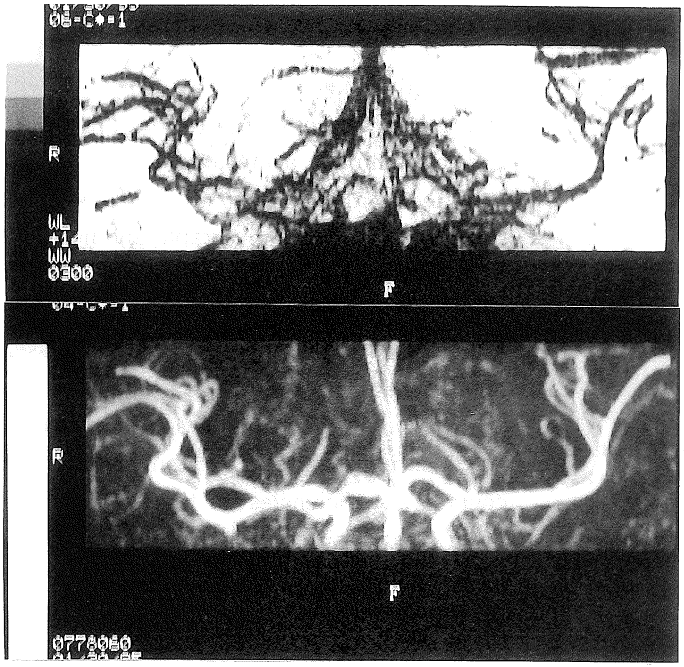
On the contradiction to the TOF and phase contrast (PC) MR angiography methods, the black appearance of blood flow in certain sequences can also be used as an advantage for generating the contrast between vessels and stationary tissues. Consequently, the drawbacks of TOF angiography in accurate visualization of venous anatomy will be accounted as efficiencies for this method[1),4)~7)].

To create dark signal of blood flow, three kinds of utilizations have been introduced by other groups[4)~7)]so far ; out flow effect with 2DSE, dephasing and preinversion methods with 3D gradient echo. Among these, using thin-section 2DSE with presaturation has been reported as effective method, however, insufficient spatial resolution and time-con-



a
b

Fig.8. The post projection images. (anterior-posterior acquisition)
a) Minimum intensity projection (mip) for 3D black blood imaging.
b) Maximum intensity projection (MIP) for 3D TOF imaging.
In mip images, vessel tracking can be accomplished better than in MIP images, reliably.



a
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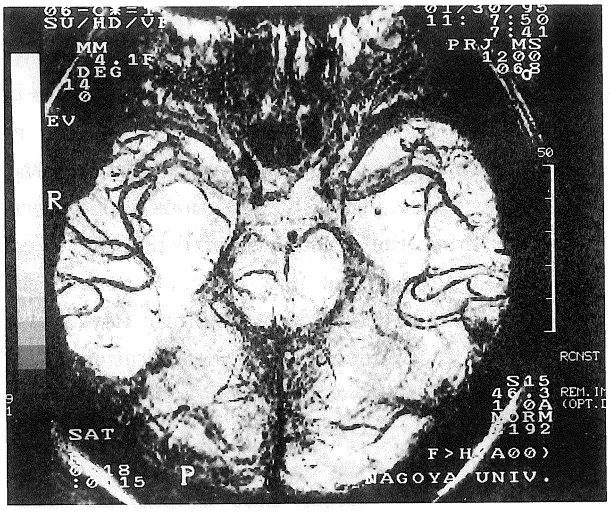
Fig.9. The post projection images (Inferior-superior acquisition). Other examples of a) mip and b) MIP imaging.

suming problems are degrading the efficiency[1),4)]. 3D gradient echo method can provide good spatial resolution, however, the susceptibility artifacts could be a problem for head imaging.

We supposed that the enough out-flow effect could not be expected if 3DFT method would be selected because the slab was rather thick. We intended to ensure flow void effect by applying presaturation pulse in addition to the intrinsic phase dispersion effect of the 3DFSE sequences, and got the acceptable results especially in the peripheral vessels. Thus, unlike to the 2DSE methods, we guess that out-flow effect is not essential for 3DFSE method. For this reason considering the v_{ave} of 36.3 cm/s (SD=8.6 cm/s)[4)] for the blood in internal carotid artery and the value of 68ms for the 4th echo as the zero encode one (echo space=17ms), the required dis-



a

b

Fig.10. The post projection images. Black blood imaging as a complementary to TOF imaging are shown in this figure. a) mip, b) MIP. The small bifurcation's trace at distal with their tiny lumen could be visualized clearly in a) mip. However, the vessels overlap with the air existence area, dura, veins or possible calcified plaques have to be prevented in this method.

tance for traveling spins before reaching to this echo would be as : $v_{ave} \times$ 4th echo time= $(\sim 50cm/s) \times (\sim 80ms) = (\sim 4cm)$, which approximately 5cm was considered as enough distance below the image slab for applying the SAT pulse.

Based on the above facts, thin-section 3DFSE sequences with presaturation pulse in this work is advantageous because, first of all, 3D acquisition could realize high resolution along the slice encoding axis, then the proximal presaturation caused the inflow of saturated spins into the vessels to yield uniform black blood signal, finally, the fast spin echo sequences with all benefits of conventional spin echo sequences could achieve the practical acquisition time.

Therefore, in accordance with above requirements, the observations of two experienced radiologists (MRA specialists) led to selection of TE values of 68ms as the optimal one. The existence of considerable signal inside the ICA lumen in shortest TE acquisition (30ms) was attributed to the rapidly moving spin which passing across the presaturation slab and still remaining within the imaging slab, causing to form a spin echo signal. While, this kind of imperfect out flow effect was no longer observed when TE was long as 68ms. Moreover, the signal-to-noise ratios, Fig.4, as the physical image quality criteria approved the above perception.

In TR optimization study with fixed TE= 68ms, the effectiveness of applied proximal presaturation in vessels detectability was attributed to this fact that ; considering the perpendicular flow to the section, and v_{max}= (section thickness)/(TE/2), with TE=68ms and slice thickness=1.6mm, the washout effect alone will cause the flow void if the velocity is greater than 4.7cm/s. The v_{ave} in internal carotid artery is 36.3cm/s (SD=8.6 cm/s)[4]. This expectation was affirmed by observing different detectability for MCA and ICA vessels in TR of 1200ms SAT (−) acquisition results. Although, TR of 1800 ms SAT (+) realized the best signal to noise ratio as well as the best contrast, considering the long acquisition time, 12min, TR of 1200ms SAT (+) was selected as a practical choice.

In comparison with standard TOF MRA, the ability of new optimal method in significantly better visualization of the branches of peripheral small vessels was considered as the most important outcome for clinical practice. Since, in small bifurcations of peripheral arteries, the dominance of dephasing effect compared to out flow effect, the strong dephasing produced by nonuniform flow vector due to turbulent flow and saturation effect due to slow flow would be advantages for this method.

However, the dark signal within carotid arteries overlapped with background signal of air, bone or possible calcified plaques, limited the vessel tracking in minimum intensity projection display. In addition, dura and veins within the skull can sometimes be obstacles for good depiction of arterial system. This implies that in the presence of an anatomic structure with similar signal intensity, vessel visualization would be impaired. Therefore, some other projection algorithm have to be replaced with the non optimal minimum intensity projection (mip) algorithm which has already been available as post processing method for BB MRA. Furthermore, the provided imaging time, 8 minutes, achieved by the optimal parameters in this method, still is twice as long as the standard TOF MRA imaging time, which could be shortened by increasing echo number.

Conclusion

We demonstrated the capability of black blood MR angiography in exploiting brain vessels. The problematic cases of TOF imaging such as slow and/or complex flow regions could be detected by high contrast and uniform flow void of this method, specially in vessel tracking of peripheral small vessels with slow flow velocity. 3DFSE sequence in axial orientation with proximal presaturation pulse (in TR=1200ms and TE=68ms) resulted better appearances of brain flow than without presaturation acquisition and TOF method. Moreover, as a time-efficient method that yields high spatial resolution black images, 3DFSE could compensate for all those drawbacks engaged with the impractical originally suggested 2DSE black blood imaging[1),4)].

This work confirmed the potential ability of the black blood MR angiography as promising complementary for TOF MR angiography in a close future. However, other proper post processing strategy such as region-growing algorithm[1),4),21)], have to be accounted instead of the conventional ray tracing method to prevent vessels' overlap with air existence area or possible calcified plaques, also depicting those arteries passing through the bone. Shortening the scan time, requires increasing the echo train length number (ETL), performing multi-slab acquisition or employing echo data conjugation[22)], which would be remained as effective suggestions for evolving this method.

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