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Comparison of tissue classification using spin-echo and fast spin-echo MRI imaging

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Comparison of Tissue Classification using Spin-Echo and Fast Spin-Echo MRI Imaging

Final Report

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Abstract

This study involves the comparison of two image acquisition sequences, the spin-echo (SE) sequence and the fast-spin-echo (FSE) sequence, used in magnetic resonance imaging (MRI). The conventional SE sequence acquires one line of k-space at a time while the FSE sequence can acquire N lines of k-space at a time. FSE scan times are therefore much faster, but the disadvantages include a lower signal-to-noise ratio and reduced accuracy. The purpose of this study is to compare T1, T2, and $\rho$ images calculated from both FSE and SE sequences and to determine if images from the FSE sequence can be corrected, if necessary. The experiment was carried out by preparing a phantom of five test targets with T1 and T2 values similar to brain tissue imaged at 1.5T. The phantom was imaged using a SE sequence and three different FSE sequences with N=8, 16, and 32. The acquisition times were 90, 30, 15, and 5 minutes, respectively. Fourteen images were acquired from each sequence and input into a computer program that generated T1, T2, and $\rho$ images. Two-dimensional T2 vs. T1 histograms were created and compared. As N increased (and scan time decreased), the clusters in the two-dimensional histograms that represented the test targets became less clearly defined and their T1 values increased.

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I thank Dr. Joseph P. Hornak for being my advisor on this project, and the Magnetic Resonance Imaging Center at the University of Rochester for use of the magnetic resonance imager.

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Introduction

This study involves the comparison of two image acquisition sequences, the spin-echo (SE) sequence and the fast-spin-echo (FSE) sequence, used in magnetic resonance imaging (MRI). The purpose of this study is to compare $T_1$, $T_2$, and $\rho$ images calculated from the FSE and SE sequences. Fletcher demonstrated a technique for tissue classification using images from the SE sequence (1). However, the data acquisition was a lengthy process. It is desirable to use a fast imaging sequence in order to reduce patient discomfort. Similar results for tissue classification may be obtained faster by using a FSE sequence. The conventional SE sequence acquires one line of k-space (spatial frequency domain) at a time while the FSE sequence can acquire N lines of k-space at a time (2). FSE scan times are therefore much faster, but the disadvantages include a lower signal-to-noise ratio and reduced accuracy. The SE sequence requires an imaging session of about ninety minutes. The FSE sequence provides similar or slightly degraded results in twenty minutes or less.

Background and Theory

Overview

The magnetic resonance imager generates an image of the inside of your body by creating a magnetic field, sending radio waves through your body, and then measuring the response. The raw data collected is used to construct images with the help of computers. Protons, electrons, and neutrons possess spin. The spin of a hydrogen nucleus is comparable to a magnetic moment vector. A nucleus must have an unpaired proton or an unpaired neutron, or both to be magnetic. The hydrogen nucleus aligns itself in the direction of a strong magnetic field. Then, radio waves stimulate the hydrogen nuclei, shown in Figure 1.

![Diagram showing magnetization vector](image)

Figure 1. The magnetization vector (a) aligns itself in the direction of a strong magnetic field. The magnetization vector rotated 90 degrees (b). The magnetization vector rotated 180 degrees (c). (3)

The gyromagnetic ratio, $\gamma$, is 42.58 MHz / T for hydrogen (4). The factors that determine the
rotation angle include $\gamma$, $\tau$, the length of time the magnetic field is on, and the magnitude of the RF magnetic field, $B_1$ (4). Equation 1 is used to determine the rotation angle (4).

$$\theta = 2\pi \gamma \tau B_1$$  Eq. 1

After stimulation by radio waves, the hydrogen nucleus re-emits the absorbed energy in the form of radio waves. A short-wave radio antenna and a receiver can detect the re-emitted waves. The hydrogen spin-lattice relaxation time $T_1$ and the spin-spin relaxation time $T_2$ define the rate at which the emitted signal fades after stimulation (3). $T_1$ is the time the Z component of the magnetization changes by a factor of $e$, shown in Figure 2. $T_1$ represents the re-emission of energy (3). $T_2$ represents the dephasing of oscillating hydrogen nuclei (3). Dephasing occurs when a group of spins swing out of phase with each other and their signals cancel. Their combined signal falls off at the rate $T_2$. $T_2$ is always less than or equal to $T_1$ (4).

Spin-Echo Pulse Sequence

In order to separate the effects of $T_1$, and $T_2$, a sequence of radio pulses is applied to the tissue. These are called pulse sequences. A common pulse sequence used in MRI is the spin-echo (SE) sequence. The sequence produces a series of raw data images of different time of repetition (TR) and time to echo (TE) parameters. First, a 90-degree pulse is applied, followed by a 180-degree pulse. Figure 3 shows an echo arriving at twice the time between the first and second pulses. It is the echo of the first 90-degree decay signal. The 180-degree pulse acts as a magnetic barrier that causes the echo.
Figure 3. The spin-echo sequence, showing a 90-degree pulse followed by a decay signal, then a 180-degree pulse. An echo of the first 90-degree decay signal arrives at twice the time between the first and second pulses. (3)

It is possible to apply more than one 180-degree pulse following a 90-degree pulse. TR is the time between two complete sequences, or the time between two 90-degree pulses. TE is the time between two echoes. Short TR and TE times result in a strong $T_1$-weighted image, while long TR and TE times produce a strong $T_2$-weighted image. The signal for a spin-echo sequence is determined using equation 2 (4).

$$S = k (1 - e^{-TR/T_1}) e^{-TE/T_2} \quad \text{Eq. 2}$$

A conventional spin-echo sequence completes one line of k-space per TR (2). K-space is a two-dimensional frequency space. The middle lines of k-space, which are low spatial-frequencies, have the greatest impact on image contrast (2). The sequence is repeated until all lines of k-space are filled. After the k-space has been filled, a two-dimensional Fourier transform is applied to the k-space data to produce an image. In Figure 4, as each echo is sampled, each line of data is placed in a separate k-space (2).
Fast Spin-Echo Pulse Sequence

A fast spin-echo (FSE) sequence uses a different phase encoding gradient for each echo generated. More than one line of k-space is completed per TR (2). The echo train length (ET) is the number of 180-degree pulses applied after the initial pulse. Increasing the ET decreases the imaging time and affects the contrast of the image (2). Figure 5 shows a FSE sequence with an ET of four. The lines closer to the middle of the k-space have a higher signal. This is shown for echo number four, which has a phase encoding gradient near the middle of the k-space.
A SE sequence requires an imaging session of about ninety minutes. These long imaging times may cause patient discomfort. A FSE sequence can take less than twenty minutes. However, the images from a FSE sequence may result in decreased contrast and blurring in T1 weighted images (2). The FSE sequence could also introduce some artifacts to the image.

For SE and FSE sequences, a series of images with a constant TR and varying TE and another series with a constant TE and varying TR is generated. T2 images are generated using the constant TR images. The T1 and $\rho$ images are generated using the constant TE images. The images are calculated by fitting a curve to the data. Tissue classification is performed by creating a three-dimensional histogram (3) of the T1, T2, and $\rho$ images. Similar tissues are grouped in clusters in the three-dimensional histograms (1), which allows different tissue types to be classified. Multispectral tissue classification (MTC) is the segmentation of tissue types in the human body using medical images. MTC results from the processing of hydrogen spin-lattice relaxation time T1, spin-spin relaxation time T2, and spin density $\rho$ images (1).

Methods
Creating a phantom

The experiment was carried out by preparing a phantom of five test targets, each with different \( T_1 \) and \( T_2 \) values. The phantom was made in the MRI lab at the Chester F. Carlson Center for Imaging Science. The layout of the test targets in the phantom is shown in Figure 6. The phantom is a PVC cylinder five inches in diameter, with five 60 ml polyethylene bottles as the test targets and two smaller polyethylene bottles filled with distilled water inside. The \( T_1 \) and \( T_2 \) values for the test targets were in the range of 0.25 s to 2 s for \( T_1 \) and 60 ms to 200 ms for \( T_2 \). These values are similar to \( T_1 \) and \( T_2 \) values for brain tissue. The test targets were made by filling the five polyethylene bottles with the following solutions (4): 0.0058 Ni (mole/L), 0.0007 Mn (mole/L), 0.0001 Mn (mole/L), 0.00022 Mn (mole/L), and 0.000073 Mn (mole/L). The phantom was placed in a 1.5 T General Electric Signa imager at the Magnetic Resonance Imaging Center at the University of Rochester. The precaution of removing metal or magnetic materials was used before entering the imaging room.

![Figure 6. Test target layout of the phantom. Numbers one through five represent the five test targets. Numbers six through eight represent distilled water. The purpose of vials six and seven is to keep the rest of the targets from moving during the imaging session.](image)

Imaging the phantom

The phantom was imaged using a SE sequence and three different FSE sequences with \( ET = 8 \), 16, and 32. The acquisition times were 90, 30, 15, and 5 minutes, respectively. The parameters for each sequence were: \( TR = 4000, 3000, 2000, 1500, 1000, 750, 500, 250 \) ms at a constant \( TE = 15 \) ms, and then \( TE = 25, 50, 75, 100, 150, 200 \) at a constant \( TR \) of 1000 ms. The acquisitions for the constant \( TR \) data were all single echo images. The transmit gain (TG) and receiver gains (R1 and R2) were fixed at the values determined for the \( TR = 4000 \) ms, \( TE = 15 \) ms SE image. TG was set a 7.90 db, R1 = 6, and R2 = 14. Increasing the ET decreases the time required for
imaging. Due to limitations of the imager, the minimum TR of the 16 ET FSE sequence was 267 ms instead of 250 ms, and the minimum TR of the 32 ET FSE sequence was 517 ms. The parameters are presented in Table 1. Only thirteen images were collected for the 32 ET FSE sequence. The total number of images for all four sequences is fifty-five. The images were stored as MR files and then converted to binary images.

![Table 1](image)

### Calculating $T_1$, $T_2$, and $\rho$ images

An IDL program originally written in Fortran by Gong, Li, and Hornak (5, 6) was used to calculate $T_1$, $T_2$, and $\rho$ images for each imaging sequence used. A block diagram of the experiment from data collection using spin-echo and FSE to tissue classification and segmentation is shown in Figure 7.
The spin-echo images have the level of quality we wish to achieve in the FSE images.

Two-dimensional (2-D) $T_2$ vs. $T_1$ histograms for each sequence were created and compared (1). The histograms are used to determine if clusters representing different tissue types, or different test targets for this experiment, begin to overlap. It is expected that the probability for overlapping clusters will increase in the higher ET FSE 2-D histograms. If the clusters overlap, it will be more difficult to classify different tissue types or the phantoms.

Results

Analysis

$T_1$, $T_2$, $\rho$ images and test target clusters in $T_2$ vs. $T_1$ histograms are shown in Figure 8. As $N$ increased (and scan time decreased), the clusters in the 2-D histograms that represented the test targets broadened and became less clearly defined and their $T_1$ values increased. Regions filled with distilled water have $T_1$ and $T_2$ values that are higher than the values for the test targets and their clusters are outside the region of interest in the histograms. The apparent increase in noise of the distilled water region is due to the limit of the calculation range of the $T_1$, $T_2$, and $\rho$ program.

Discussion

Similar values calculated for $\rho$ confirms that the $T_1$, $T_2$, $\rho$ program is working correctly. This is because the test targets are water-based and have spin-density $\rho$ values close to the background of distilled water (regions 6,7, and 8 in Figure 6). The clusters in the 2-D $T_2$ vs. $T_1$ histogram for
the N = 32 FSE sequence in Figure 8 show that image segmentation is possible with decreased acquisition time. Each test target can be separated by defining a boundary around each cluster. The general trend for increasing N is for T1 values to increase, and for clusters in the 2-D histograms to become broader. The increase in T2 values for the test targets is minor as N increases. However, the N = 8 FSE sequence does not fit the trend. For test targets three and four (referring to Figure 6) of the N = 8 FSE sequence, the T1 values actually decrease from the SE sequence. Also, the T2 values for the N = 8 FSE sequence are higher than corresponding T2 values in the other sequences. It is not clear why this anomaly occurs for the N = 8 FSE sequence. Further research is required to determine the cause. A problem encountered with the IDL program for computing T1, T2, ρ images involved the setting of the minimum and maximum T2 values for the program to calculate. If the maximum set T2 value is too low, the program sets the overflow pixels to zero. This was most noticeable in the FSE sequence images, which had higher T2 values in the distilled water regions (regions 6, 7, and 8 in figure 6). If the minimum T2 value is too low, the program would take much longer to find the zero crossing point of the linear least-squares algorithm or it would never find it. The IDL program calculates the T1, T2, ρ images for each sequence in about forty minutes on a SUN UNIX platform. Since processing time per sequence is about forty minutes, there is still some room for optimization of the code to run more efficiently.

Conclusions

The trend for increasing N of the FSE sequences (increase in T1 values and similar T2 values to the SE sequence) does not apply for the N = 8 FSE sequence. Therefore, it would be difficult, if not impossible, to assign a correction factor to the T1, T2, ρ images from the FSE sequences to approximate T1, T2, ρ images from the SE sequence. Future research should focus on determining the cause of the anomaly in the trend, and on optimizing the IDL program to compute T1, T2, ρ images faster. In addition, the experiment should be repeated, this time imaging the brain region of a human subject to determine if tissue classification is possible with FSE sequences. On a positive note, the 2-D T2 vs. T1 histogram for the N = 32 FSE sequence demonstrates that image segmentation of test target clusters is possible at an acquisition time of only five minutes compared to the SE sequence acquisition time of ninety minutes.
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Appendix A: The IDL Code

The IDL code used to calculate T1, T2, and ρ images from each of the imaging sequences (SE, and N=8, N=16, and N=32 FSE sequences).

Appendix B: Instructions for using T1T2rho program

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IDL Code

```
FUNCTION Z, T, NT1, TR, SE
  B1 = fltARR(10)
  C1 = fltARR(10)
  Z = 0.
  For M = 0, NT1 - 1 do begin
    EE = EXP(-TR(M)/T)
    B1(M) = TR(M)*EE
    C1(M) = 1. - EE
  endfor
  For M = 0, NT1 - 1 do begin
    For N = 0, NT1 -1 do begin
      Z = Z + B1(N)*C1(M)*(C1(N)*SE(M) - C1(M)*SE(N))
    endfor
  endfor
  Return, Z
END

FUNCTION Z1, T, NT2, TE, SE
  C1 = fltARR(10)
  B1 = fltARR(10)
  D1 = fltARR(10)
  Z1 = 0.
  For M = 0, NT2 - 1 do begin
    B1(M) = EXP(-TE(M)/T)
    C1(M) = TE(M) * B1(M)
    D1(M) = B1(M) * B1(M)
  endfor
  For M = 0, NT2 - 1 do begin
    For N = 0, NT2 -1 do begin
      Z1 = Z1 + B1(N)*C1(M) * (C1(N)*SE(M) - C1(M)*SE(N))
      D1(M) = B1(M) * B1(M)
    endfor
  endfor
  Return, Z1
END
```
endfor

Return, Z1
END

;*********************************************************************************************************

pro t1t2rhov5

RHS = 1.
T1MIN = 0.11
T1MAX = 20.0
T2MIN = 0.011
T2MAX = 100.
STT = fltarr(65536)
ST = fltarr(65536)
IRHO = fltarr(256,256)
SE = fltarr(10)
IJK = fltarr(256)

;*********** Open DAT file and read in Data ******

ff=dialog_pickfile(/read, filter="*.DAT")
mytemp=CREATE_STRUCT('Version',float(1),'datastart',$
   long(0),'delimiter',byte(44),'missingvalue',$
   !Values.F_NaN,'commentsymbol','','fieldcount',$
   long(2),'fieldtypes',[7,7],'fieldnames',$
   ['field1','field2'],'fieldlocations',$
   long([0,2]),'fieldgroups',[0,1])
data = READ_ASCII(ff, TEMPLATE=mytemp)
print, data.field1
print, data.field2
constantTR=data.field2[0]
ITRC = constantTR
NT2=data.field1[0]; number of t2 images
t2images = data.field2[1:NT2]
T2outputfile = data.field1[NT2+1]

NT1 = data.field1[NT2+2]; number of t1 images
ConstantTE = data.field2[NT2+2]
ITEC = ConstantTE
t1images = data.field2[NT2+3:]*
xy = fix(NT2)
xx = fix(NT1)
T1outputfile = data.field1[xx+xy+3]
RH0outputfile = data.field1[xx+xy+4]

SET2 = fltarr(xy,256,256)
SET1 = fltarr(xx,256,256)

cd, dialog_pickfile(/directory)
; change to directory with the MRI data images
swap = DIALOG_MESSAGE('Do you want to swap bytes?$', question=1)

for i=0,xy-1 do begin
  openr, unit, t2images[i], /get_lun
  image2 = intarr(256,256)
  readu, unit, image2
  close, unit
  free_lun, unit
  SET2[i,*,*] = image2[*,*]
  if swap eq 'Yes' then $ SET2[i,*,*] = swap_endian(image2[*,*])
endfor

window, 2, xsize = 256, ysize = 256
tvscl, SET2[XY-1,*,*]

for i=0,xx-1 do begin
  openr, unit, t1images[i], /get_lun
  imagel = intarr(256,256)
  readu, unit, imagel
  close, unit
  free_lun, unit
  SET1[i,*,*] = imagel[*,*]
  if swap eq 'Yes' then SET1[i,*,*] = swap_endian(imagel[*,*])
endfor

window, 1, xsize = 256, ysize = 256
tvscl, SET1[XX-1,*,*]

;****Calculate MIN Signal Cut Off for T2 & T1 ***********

box_cursor, llx, lly, xsize, ysize
llx=fix(llx)
lly=fix(lly)
xs=fix(xsize)
ys=fix(ysize)
window, title = 'histogram of background'
scot1 = max(SET1[*,llx:llx+xs,lly:lly+ys]) *NT1
scot2 = max(SET2[*,llx:llx+xs,lly:lly+ys]) *NT2
print, 'scot1 = ',scot1
print, 'scot2 = ', scot2

TE = data.field1[1:xy]/1000.
TR = data.field1[xy+3:xy+2+xx]/1000.

set2 = reform(set2, nt2, n_elements(set2)/nt2)
set1 = reform(set1, nt1, n_elements(set1)/nt1)

;********Calculate T2 DATA Matrix ***********************

IF(nt2 EQ 0) then goto, jumpt1
IF(nt2 EQ 1) then begin
  stt = set2[0, *]
  goto, jumpt1
endif

TimeT2 = SYSTIME(1)
print, 'calculating T2'
For I=0L, 65535 do begin
  TMIN = T2MIN
  TMAX = T2MAX
  Sum = 0.
  se = set2[* ,i]
  SUM = total(se)
  A = Z1(TMIN, NT2, TE, SE)
  B = Z1(TMAX, NT2, TE, SE)
  IF((A*B GE 0.) or (SUM LE SCOT2)) then begin
    T2 = 0.
  endif else begin
    jumphere:
    T = (TMIN*B-TMAX*A)/(B-A)
    C = Z1(T, NT2, TE, SE)
    IF((A*C LT 0.) AND (ABS(C) GT 0.0001)) then begin
      B = C
      TMAX = T
      goto, jumphere
    endif else begin
      IF((B*C LT 0.) AND (ABS(C) GT 0.0001)) then begin
        A = C
        TMIN = T
        goto, jumphere
      endif else begin
        T2 = T
      endelse
    endelse
  endelse
STT(I) = T2
print, I
endfor

print, 'Finished calculating T2.'
PRINT, SYSTIME(1) - TimeT2, ' Seconds'
TimeT2 = SYSTIME(1) - TimeT2

;**** storing T2 data ********************************
stt2=stt*10000
stt3=long(stt2)
stt3 = reform(stt3,256,256)
WRITE_TIFF,T2outputfile,stt3,/LONG

;****************Calculate T1*************************

jumpt1:
IF (NT1 EQ 0) then goto, jumpend

print, 'calculating T1'
TimeT1 = SYSTIME(1)
For I=0L,65535 do begin
  TMIN = T1MIN
  TMAX = T1MAX
  Sum = 0.
  se = set1[*,i]
  SUM = total(se)
  A = Z(TMIN, NT1, TR, SE)
  B = Z(TMAX, NT1, TR, SE)
  IF((A*B GE 0.) or (SUM LE SCOT1)) then begin
    T1 = 0.
  endif else begin
  jumphere1:
    T = (TMIN*B-TMAX*A)/(B-A)
    C = Z(T, NT1, TR, SE)
    IF((A*C LT 0.)AND(ABS(C) GT 0.0004))$ then begin
      B = C
      TMAX = T
      goto, jumphere1
    endif else begin
      IF((B*C LT 0.) AND $(ABS(C) GT 0.0004)) $ then begin
        A = C
        TMIN = T
        goto, jumphere1
      endif else begin
        T1 = T
      endelse
    endelse
  endelse
ST(I) = T1
print, I
print, 'Finished calculating T1.'
PRINT, SYSTIME(1) - TimeT1, ' Seconds'
TimeT1 = SYSTIME(1) - TimeT1

;**** storing T1 data ****************************
st2=st*1000
st3=fix(st2)
openw, lun, T1outputfile, /GET_LUN
writeu, lun, st3
close, lun
free_lun, lun
IF(NT2 EQ 0) then goto, jumpend

;******************Calculate RHO ****************************

jump rho:

print, 'calculating rho'

TEC = Float(ITEC)/1000. ; itec is 15

I = 0L
For KI = 0, 255 do begin
  For KII = 0, 255 do begin
    I = I+1
    IF (I EQ 65536) then goto, endrho
    IF((ST(I) LE 0.001) OR (STT(I) LE 0.001)) then begin
      IRHO(KI,KII) = 0
      goto, endrho
    endif
    SY=0.
    SYY=0.
    For KKK = 0, NT1-1 do begin
      PAR = 1. - EXP(-TR(KKK)/ST(I))
      SY = Temporary(SY) + set1[KKK,I]*PAR
      SYY = Temporary(SYY)+PAR*PAR
    endfor
    IRHO(KI,KII) = fix(((SY/SYY)/$
                      EXP(-TEC/STT(I)))*RHS)
  endfor
endfor
IRHO = fix(temporary(IRHO))
print, 'Finished calculating rho.'
irho = rotate(irho,4)

;**************** storing rho ****************************

openw, lun, RHOoutputfile, /GET_LUN
writeu, lun, irho
close, lun
free_lun, lun

;******************* End of Program ****************************

jump end:
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Instructions for using the IDL program

The IDL program to calculate $T_1$, $T_2$, and $\rho$ images requires two series of MRI images saved in BIN format. The first series is the set of constant TR varying TE images, and the second series is the set of constant TE and varying TR images. The filenames of the images and the imaging parameters and then recorded in a DAT file. An example of such a DAT file is shown in the sample DAT file link.

Sample DAT file

In the sample DAT file, the first number is the number of constant TR varying TE images (6 in this example), and the next number (1000) is the TR value (ms). The next lines are the TE values (ms) followed by the image filenames. The following line is the filename the user specifies for storage of the calculated $T_2$ image. In this example, the calculated $T_2$ image was stored as a TIF file as the values were quite large. The process is repeated for the constant TE and varying TR images. The number of images (8) and the TE value (15 ms) is entered. Then, the TR values (ms) followed by the image filenames are entered. The next line is the filename the user specifies for storage of the calculated $T_1$ image, and the last line is the filename for the $\rho$ image, both stored in BIN format for this example.

Running the code:

1. Open the program in IDL and compile.
2. Run the program either by typing "t1t2rhov5" at the command line or by clicking on the run icon.
3. The program prompts the user for the DAT file with the image filenames. Select the DAT file.
4. The program prompts the user for the directory where the image files are stored. Select a directory.
5. The program will ask the user whether to swap bytes or not. If the user is not sure, make a selection and the program will open two images. If the background in the image is not black, restart the program and make a different selection.

6. A box cursor will appear in the center of one of the two images opened. Left click and move the box cursor with your mouse to a background region, typically the corner of the image. Then right click to enter. The program then finds the maximum value in the box cursor region and sets the noise level to that value.

7. Now, the program will calculate the $T_1$, $T_2$, and $\rho$ images and store them under the filenames specified in the DAT file. Run time is approximately 40 minutes total on a SUN UNIX workstation.

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**Figure 8:** $T_1$, $T_2$, $\rho$ images and test target clusters in $T_2$ vs. $T_1$ histograms

**SE sequence**

$N = 8$ FSE sequence

$N = 16$ FSE sequence

$N = 32$ FSE sequence
FSE  T1  N=16  T2