SUPPLEMENTAL DIGITAL CONTENT 1

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% Wavelet Transform Modulus Maxima Calculator for Matlab (WTMM_Calc)
% Copyright (C) 2010-11 Dr SM Bishop, University of Cambridge, Division
of Anaethesia
% Author: Steven Bishop, smb50 'AT' cantab.net
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% Dependencies:
% Requires
%   1. FastSmooth.m by Tom O'Haver (22nd May 2008). Available from:
%        http://www.mathworks.com/matlabcentral/fileexchange/19998-fast-
smoothing-function
%   2. Wavelet Toolbox for Matlab (tested with v4.1). Available from:
%        http://www.mathworks.co.uk/products/wavelet/
% NB: this code has only been tested against Matlab v7.5.0 and the above
dependencies
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% To use:
%   1. Remove the .txt extension from the .m files
%   2. Place the .m files in your Matlab working directory and ensure the
above
%      dependencies are installed and available to Matlab
%   3. Call WTMM_calc(...) with appropraite arguments e.g.
%      WTMM_calc('~/hrdata.txt', false, 3, 32, true, -8, +8, true)
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SUPPLEMENTAL DIGITAL CONTENT 2

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Version 3, 29 June 2007

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SUPPLEMENTAL DIGITAL CONTENT 3

```
% ---------------------------------------------------------------------------
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% Copyright (C) 2010-11 Dr SM Bishop, University of Cambridge, Division
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% ---------------------------------------------------------------------------
------------


% -----
% WTMM_calc(file, maxscale, detrend, fitstart, fitend, multi, minq, maxq,
verbose)
% file - string containing path of file to analyse
% maxscale - maximum scale to perform the wavelet transform over
% detrend - boolean. True = will perform cubic spline detrending of
%            respiratory artefact (BAD IDEA!)
%          -> detrending appears to make everything (incl gaus noise)
%          artifically differentiable with a h_max circa 1.0
% fitstart - minimum scale for supremum lines and fitting partition
functions
% fitend - maximum scale for fitting partition functions
% multi - if true, include zero & negative moments (q's)
% minq - minimum moment (min_q)
% maxq - maxmimum moment (max_q)
% verbose - display all graphs; output runtime information
% -----


function WTMM_calc(file, maxscale, detrend, fitstart, fitend, multi,
minq, maxq, verbose)


% ---
% Define a few important global values
% ---
SCALE_MAX = maxscale;
```

```
FIT_START = fitstart;
FIT_MAX = fitend;
scale_range = 1:SCALE_MAX;
wavelet = 'gaus3';


% ---
% Create vector of moments
% ---
if multi
    Q = linspace(minq,maxq,101);
else
    Q = linspace(minq,maxq,31);
end
sizeQ = length(Q);


% ---
% Reset a few recycled vars
% ---
WT = [];
data = [];
z = [];
log_j = [];
log_z = [];
Y_S = [];
T = zeros(sizeQ,1);
newTau = zeros(sizeQ,1);
h = zeros(sizeQ-2,1);
D = zeros(sizeQ-2,1);
Q_new = Q(2:sizeQ-1);


% ---
% Import the data, calculate its size and ensure its length is even and
% divisible by 4
% ---
data = importdata(file);
SIZE_DATA = length(data);
if mod(SIZE_DATA, 4) ~= 0
    data = data(1:SIZE_DATA-mod(SIZE_DATA,4));
    SIZE_DATA = length(data);
end
SIZE_DATA


% ---
% If in verbose mode then display the data
% ---
if verbose
    plot(data);
    xlabel('Heart beats [time]');
    ylabel('MAP [mmHg]');
    pause;
```

```
end


% ---
% (Optionally) Detrend the data
% ---
if detrend
  data2 = MaximaDetrend(data, verbose);
  %%data = data - data2;
end


% ---
% Rescale the data
% ---
m1 = min(data);
m2 = max(data);
data = 0.2 * (data-m1)/(m2-m1) + 0.4;


% ---
% Apply padding - this helps to prevent strong singularities being found
at
% the edge of the data following the WT
% ---
b = zeros(SIZE_DATA*2, 1);
for i = 1:(SIZE_DATA/2)
    b(i) = data(1);
end
for i = (SIZE_DATA/2 + 1):(SIZE_DATA*3/2)
   b(i) = data(i - SIZE_DATA/2);
end
for i = (SIZE_DATA*3/2 + 1):(SIZE_DATA*2)
    b(i) = data(SIZE_DATA);
end
data = b;
SIZE_DATA = length(data);


% ---
% If in verbose mode display the padded data
% ---
if verbose
    plot(data);
    pause;
end


% ---
% Perform the wavelet transform
% ---
if verbose
    WT = cwt(data, scale_range, wavelet, 'plot');
    pause;
```

```
else
    WT = cwt(data, scale_range, wavelet);
end

WT = abs(WT);


% ---
% Remove the padding from around the wavelet matrix
% ---
depad_WT = zeros(SCALE_MAX, SIZE_DATA/2);
count = 1;
for i = SIZE_DATA/4+1:SIZE_DATA*3/4
    for s = scale_range;
        depad_WT(s, count) = WT(s, i);
    end
    count = count + 1;
end
WT = depad_WT;
SIZE_DATA = SIZE_DATA/2;


% ---
% Smooth the wavelet transform matrix
% ---
smoothed_WT = WT;
smooth_scales=linspace(1,10,SCALE_MAX);
for s = scale_range
    tmp = WT(s:s, 1:SIZE_DATA);
    smoothed_WT(s,:) = FastSmooth(tmp,smooth_scales(s),2,1);
end
WT = smoothed_WT;


% ---
% Find the local maxima (and plot if in verbose mode)
% ---
local_maxima = zeros(size(WT));

for s = scale_range
  for d = 2:(SIZE_DATA-1)
    if WT(s:s, d) > WT(s:s, d-1) & WT(s:s, d) > WT(s:s, d+1)
      local_maxima(s:s, d) = WT(s:s, d);
    end
  end
  if WT(s:s, 1) > WT(s:s, 2)
    local_maxima(s:s, 1) = WT(s:s, 1);
  end
  if WT(s:s, SIZE_DATA) > WT(s:s, SIZE_DATA-1)
      local_maxima(s:s, SIZE_DATA) = WT(s:s, SIZE_DATA);
  end
end

if verbose
```

```
    [lineRows, lineCols] = find(local_maxima(1:SCALE_MAX, 1:SIZE_DATA));
    plot(lineCols, lineRows, 'marker', '*', 'markersize', 2, 'linestyle',
'none', 'color', 'k');
    title('Maxima');
    pause;
end


maxlines = FindNearest_breadthfirst(local_maxima, FIT_START, verbose);

if verbose
    [lineRows, lineCols] = find(maxlines(1:SCALE_MAX, 1:SIZE_DATA));
    plot(lineCols, lineRows, 'marker', '*', 'markersize', 2, 'linestyle',
'none', 'color', 'k');
    title('Maxima lines');
    pause;
end


% ---
% Update the maxlines with their supremum (and plot if in verbose mode)
% ---
Y_S = zeros(size(maxlines));
Y_S = SubstSupremum(maxlines, WT, FIT_START);

if verbose
    [lineRows, lineCols] = find(Y_S(FIT_START:FIT_MAX, 1:SIZE_DATA));
    plot(lineCols, lineRows, 'marker', '*', 'markersize', 2, 'linestyle',
'none', 'color', 'k');
    xlabel('Heart beats [time]');
    ylabel('Scale [time]');
    pause;
end


% ---
% Calculate the partition function over scale FIT_START to SCALE_MAX
% ---
count = 1;
z = zeros(length(Q), SCALE_MAX);
for q = Q
  for scale = FIT_START:SCALE_MAX
    sum = 0;
    for col = 1:SIZE_DATA
      if Y_S(scale, col) > 0
        sum = sum + (abs(Y_S(scale, col))^q);
      end
    end
    z(count,scale) = sum;
  end
  count = count+1;
end
```

```
% ---
% If verbose mode - plot the partition functions
% ---
if verbose
    log_s = log(FIT_START:FIT_MAX)/log(10);
    c = linspace(0.1, 0.7, sizeQ);
    colors = [c; 1-c; c];
    figure;
    hold on;
    count = 1;
    xlabel('log(scale)');
    ylabel('log(Z(q, scale))');
    title('Plot of the partition function for orders q against scale');
    for q = Q
       plot(log_s, log(z(count:count, FIT_START:FIT_MAX))/log(10),
'marker', '*', 'markersize', 3, 'linestyle', 'none', 'color',
colors(:,count:count));
       count = count+1;
    end
    hold off;
    pause;
end


% ---
% Linear fit the partition functions to calculate Tau(q)
% ---
count = 1;
for q = Q
   [PP, QQ] = polyfit(log(FIT_START:FIT_MAX)/log(10), log(z(count:count,
FIT_START:FIT_MAX))/log(10), 1);
   T(count) = PP(1);
   count = count+1;
end

% ---
% If verbose, plot tau(q) against q
% ---
if verbose
    plot(Q, T, 'marker', '*', 'markersize', 2, 'linestyle', 'none',
'color', 'k');
    xlabel('q');
    ylabel('T(q)');
    pause;
end


% ---
% Calculate h(q) and rerange T(q)
% ---
incount = 2;
outcount = 1;
for q = Q_new
    newTau(outcount) = T(incount);
```

```
    h(outcount) = (T(incount+1)-T(incount-1))/(Q(incount+1)-Q(incount-
1));
    incount = incount+1;
    outcount = outcount+1;
end


% ---
% Calculate D(h)
% ---
count = 1;
for q= Q_new;
    D(count) = Q_new(count)*h(count) - newTau(count);
    count = count+1;
end


% ---
% If verbose, plot the singularity spectrum
% ---
maxHval = ceil(max(h));
minHval = floor(min(h));
maxDval = ceil(max(D));
minDval = floor(min(D));
if verbose
    plot(h, D, 'marker', '*', 'markersize', 2, 'linestyle', 'none',
'color', 'k');
    xlabel('h');
    ylabel('D(h)');
    title('Singularity Spectrum');
    axis([minHval maxHval minDval maxDval]);
    pause;
end


% ---
% Linear bestfit the singularity spectrum and calculate curve parameters
% Find the regions where h and D increase monotonically
% ---

numpoints = length(h);

% Find points from positive qs that behave: h(i...numpoints),
D(i...numpoints)
for i=numpoints:-1:2
   if h(i) > h(i-1) || D(i) > D(i-1)
       break
   end
end
% Find points from negative qs that behave: h(1...j), D(1...j)
for j=i:-1:2
   if h(j-1) < h(j)
       break
   end
```

```
end

new_range = [i:numpoints];
new_range = [1:numpoints];

fitp = polyfit(h(new_range),D(new_range),6);
h_max = fminbnd(@(x) -polyval(fitp,x), min(h(new_range)),
max(h(new_range)))  % maximum is inverse of minimisation problem
d_max = polyval(fitp, h_max)
h_hwhh1 = fminbnd(@(x) abs(d_max/2-polyval(fitp,x)), min(h(new_range)),
h_max);
h_hwhh2 = fminbnd(@(x) abs(d_max/2-polyval(fitp,x)), h_max,
max(h(new_range)));
hwhh = h_hwhh2 - h_hwhh1
hwhh_ratio = abs((h_hwhh2-h_max)/(h_max-h_hwhh1))
hold on
maxHval = ceil(max(h(new_range)));
minHval = floor(min(h(new_range)));
maxDval = ceil(max(D(new_range)));
minDval = floor(min(D(new_range)));
if minDval < 0
    minDval = 0;
end

% ---
% Plot the singularity spectrum
% ---
xlabel('h');
ylabel('D(h)');
title('Singularity Spectrum');
axis([-0.2 1.8 0 1.4]);
plot(h(new_range), polyval(fitp, h(new_range)));
pause;

end
```

SUPPLEMENTAL DIGITAL CONTENT 4

```
% ---------------------------------------------------------------------------
------------
% Wavelet Transform Modulus Maxima Calculator for Matlab (WTMM_Calc)
% Copyright (C) 2010-11 Dr SM Bishop, University of Cambridge, Division
of Anaethesia
% Author: Steven Bishop, smb50 'AT' cantab.net
%
% This file is part of WTMM_Calc
%
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% along with WTMM_Calc.  If not, see <http://www.gnu.org/licenses/>.
% ---------------------------------------------------------------------------
------------

% -----
% MaximaDetrend(data, verbose)
% Fit a cubic spline to data and perform respiratory detrending
% data - data vector
% verbose -  display all graphs; output runtime information
% -----

function d = MaximaDetrend(data, verbose)

% Initialise variables
a = data;
SIZE_DATA = length(data);
goingup = false;
plateau = false;
plateau_count = 0;


% ----
% Peak finding algorithm:
% ----

if a(1) < a(2)
    goingup = true;
end
maxima = a(1);
maxima_count = 1;
maxima_data = zeros(SIZE_DATA,2);
```

```
for x=2:SIZE_DATA
    if a(x) > a(x-1)
        if goingup
            maxima = a(x);
            plateau = false;
        else
            goingup = true;
            plateau = false;
            maxima = a(x);
        end
    else
    if a(x) == a(x-1)
        if goingup
           plateau = true;
           plateau_count = plateau+1;
        else
           plateau = false;
        end
    else  % a(x) < a(x-1)
        if goingup %we've just started going down from maxima
            goingup = false;
            %store next maxima
            if plateau
               for i = 1:plateau_count
                  maxima_data(maxima_count,:) = [maxima; x-
plateau_count+i];
                  maxima_count = maxima_count + 1;
               end
               plateau_count = 0;
               plateau = false;
            else
               maxima_data(maxima_count,:) = [maxima; x];
               maxima_count = maxima_count + 1;
               plateau_count = 0;
            end
        else  %or we were going down anyway
            plateau = false;

        end

    end
    end

end

% ----
% Plot the maxima data
% ----
if verbose
  figure;
  plot(maxima_data(1:maxima_count-1,1:1));
  pause;
end
```

```
% ----
% Fit a cubic spline
% ----
X = maxima_data(1:maxima_count-1, 2:2);
Y = maxima_data(1:maxima_count-1, 1:1);
cs = spline(X, Y);
spline_fit = ppval(cs, 1:SIZE_DATA);

if verbose
    figure;
    hold on;
    plot(a, 'color', 'black');
    plot(spline_fit, 'color', 'red');
    title('Spline fit of detrending compared wtih original data');
    hold off;
    pause
end

% ----
% Return the spline fit
% ----
d = spline_fit;

end
```

SUPPLEMENTAL DIGITAL CONTENT 5

```
% -----------------------------------------------------------------------
------------
% Wavelet Transform Modulus Maxima Calculator for Matlab (WTMM_Calc)
% Copyright (C) 2010-11 Dr SM Bishop, University of Cambridge, Division
of Anaethesia
% Author: Steven Bishop, smb50 'AT' cantab.net
%
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% -----------------------------------------------------------------------
------------


% ----
% SubstSupremum(chainedmaxima, wtmm, startScale)
% chainedmaxima - matrix of lines of maxima from finest to coarsest
scales
% wtmm - matrix containing wavelet transform modulus maxima
% startScale - finest scale to start supremum substitution at
% ----

function supremum_lines = SubstSupremum(chainedmaxima, wtmm, startScale)

% ----
% Get the number of scales (nscales) and length of data (ncols)
% ----
[nscales, ncols] = size(chainedmaxima);
wtmm = abs(wtmm);


% ----
% Initialisation
% ----
supremum_lines = zeros(size(chainedmaxima));

if startScale >= nscales
    fprintf('SubstSupremum error: startScale > nscales');
    return
end
```

```
% ----
% Initiate the first (finest) scale (startScale)
% ----
for i = 1:ncols
   if chainedmaxima(startScale, i) > 0
      supremum_lines(startScale, i) = wtmm(startScale, i);
   end
end

% ----
% Do for all the coarser scales
% ----
for s = startScale+1:nscales
   for i = 1:ncols
       if chainedmaxima(s,i) > 0  % This is a point on a maxima line
           % Find the maximum of wtmm(s,i) and all the sub-chains of
maxima
           % that point to it from finer scales
           max = wtmm(s,i);
           for j = 1:ncols
              if chainedmaxima(s-1, j) == i   % lower scale maxima points
to it
                 if wtmm(s,j) > max
                    max = wtmm(s,j);
                 end
              end
           end
           supremum_lines(s,i) = max;
       end
   end
end
```

SUPPLEMENTAL DIGITAL CONTENT 6

```
% ------------------------------------------------------------------------
------------
% Wavelet Transform Modulus Maxima Calculator for Matlab (WTMM_Calc)
% Copyright (C) 2010-11 Dr SM Bishop, University of Cambridge, Division
of Anaethesia
% Author: Steven Bishop, smb50 'AT' cantab.net
%
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% ------------------------------------------------------------------------
------------


% -----
% FindNearest_breadthfirst(maxmap, minscale, verbose)
% maxmap - matrix containing wavelet transform modulus maxima
% minscale - smallest scale to include in the search
% verbose - display all graphs; output runtime information
% -----

function new_maxLines = FindNearest_breadthfirst(maxmap, minscale,
verbose)

% Get the number of scales (nscales) and length of data (ncols)
[nscales, ncols] = size(maxmap);

% Display the maxmap, if in verbose mode
if verbose
  [sc, po] = find(maxmap);
  plot(po, sc, 'marker', '*', 'linestyle', 'none');
end

% Empty map of connected maxima lines
maxLines = zeros(size(maxmap));

% Populate connection map with all the points at the coarsest scale
maxLines(nscales:nscales,:) = maxmap(nscales:nscales, :);
% Ensure these are terminators of the chain, ie with a value >ncol
% (arbitarily ncols*10)
[tmp, coarse_scale_positions] = find(maxLines(nscales:nscales,:));
```

```
for i = coarse_scale_positions
   maxLines(nscales, i) = ncols*10;
end

% ----
% Main loop:
% Start at the most coarse scale and work towards finest
% ----
for s = nscales:-1:minscale+1
    thisscale = maxmap(s:s,:);
    nextscale = maxmap(s-1:s-1,:);

    [tmp, this_scale_pos] = find(thisscale);  %indices of maxima at this
(coarser) scale
    [tmp, next_scale_pos] = find(nextscale);  %indices of maxima at next
finest scale
    [tmp, number_at_scale] = size(this_scale_pos);  %number of maxima at
this scale

    % Storage for a list of pairs of indices linking an element at pos i
at this
    % scale to its nearest neighbour at pos j at nextscale seperated by
    % closest distance d (stored as (d,i,j))
    unsorted_list = zeros(number_at_scale, 3);

    counter = 1;
    % For each i in this_scale_pos find its nearest neighbour's position
    % next_scale_pos(pos) at nextscale. Their distance is dist.
    for i=this_scale_pos
           distances = i-next_scale_pos;
           [dist, pos] = min( abs(distances) );
           unsorted_list(counter, :) = [dist; i; next_scale_pos(pos)];
           counter = counter + 1;
    end

    % Need to link the __most__ nearest points first, therefore sort into
    % ascending order of distance (ie sort col 1 first then, cols 2,3)
    sorted_list = sortrows(unsorted_list,[1 2 3]);

    % Do the linking from nextscale (finer) to thisscale (coarser)
    for l = 1:number_at_scale   %for each pair of neighbours, starting
with closest pairs
        sl = sorted_list(l:l,:);
        dist = sl(1); i = sl(2); j = sl(3);
        if maxLines(s-1,j) == 0
           maxLines(s-1, j) = i;
        end
    end
end


% ----
% Do the pruning:
% Prune the lines from coarser scales that don't connect to the
```

```
% lowest scale. Do this by tracing up from the bottom (finest scale)
% ----
new_maxLines = zeros(size(maxmap));

[tmp, finest_scale_positions] = find(maxLines(minscale:minscale,:));

% For every chain starting at the finest scale
for i = finest_scale_positions
    new_maxLines(minscale,i) = maxLines(minscale,i);
    x = maxLines(minscale,i);

    % Trace the chain through the scales
    for s = minscale+1:nscales
        if x > 0  % if it traces to next level
            if maxLines(s, x) == 0 % it currently terminates here
                % Is there a line that starts nearby on this level?
                nearby = false;
                nearcount = 1;
                near_col = [];
                min1 = x-10;
                max1 = x+10;
                if min1 < 1
                    min1 = 1;
                end
                if max1 > ncols
                    max1 = ncols;
                end
                for j = min1:1:max1
                   if s ~= nscales && maxLines(s+1, j) > 0  %look at
nearby lines
                       nearby = true;     %assume it starts at scale s
                       near_col(nearcount) = j;
                       nearcount = nearcount + 1;
                   end
                end
                % If yes, then join it to make a continuous line
                if nearby
                    new_maxLines(s, x) = min(near_col);
                    x = new_maxLines(s, x);
                else
                    %else terminate this line
                    new_maxLines(s, x) = ncols*10;
                    x = 0;
                end
            else    % else it continues thus add next index
                new_maxLines(s, x) = maxLines(s, x);
                x = new_maxLines(s, x);
            end
        else
            break  % chain has terminated
        end
    end
end
end
```