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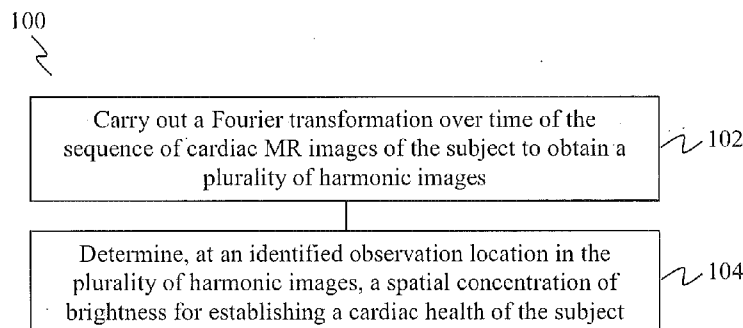


FIG. 1A

(57) Abstract: According to embodiments of the present invention, a method for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject is provided. The method includes carrying out a Fourier transformation over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images, and determining, at an identified observation location in the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject. According to further embodiments of the present invention, a device for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject is also provided.

METHOD AND DEVICE FOR ANALYZING A SEQUENCE OF CARDIAC MAGNETIC RESONANCE (MR) IMAGES

Cross-Reference To Related Application

5 [0001] This application claims the benefit of priority of Singapore patent application No. 10201401423Y, filed 10 April 2014, the content of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

10 [0002] Various embodiments relate to a method for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject, a device for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject and a computer readable medium.

Background

15 [0003] Cardiovascular Disease (CVD) is currently the leading cause of death, killing about 17.3 million people worldwide each year. This figure represents one-third of total death, a proportion that is increasing. By 2030, it may be expected that CVD may kill about 23.6 million people annually.

20 [0004] Magnetic resonance (MR) imaging technique enables physicians or medical professionals to examine the anatomy and function of the heart non-invasively. To diagnose a certain disease from the cardiac MR images, the physicians or medical professionals need to acquire a number of measurements such as the ventricular volumes over the cardiac cycle, ventricular ejection fraction, cardiac output, peak ejection rate, filling rate, myocardial wall thickening, and so on. All these measurements typically require a dynamic cardiac model. The prerequisite of the cardiac model construction is chamber segmentation.

25 [0005] The segmentation task has been traditionally performed manually via software assistance, which is time-consuming and tedious. For example, a trained clinician may

delineate one image in half a minute and it may take him/her more than one hour to complete the whole data set of typically 11 slices by 25 frames. Furthermore, the results may often be subject to a high intra/inter clinician variability. Over the past decade, automation of this tedious yet significant procedure has received a lot of attention from not only the medical imaging but also the computer vision community. Studies have been carried out but there is yet to have an algorithm or a method to robustly and precisely segment the chambers. There remains the difficulty of precise and robust automatic segmentation.

[0006] Cardiac cine MR images are acquired from the various cardiac phases throughout the whole cardiac cycle. The varying pixel intensity represents the dynamic cardiac motion. The stationary regions possess a nearly identical pixel intensity for the whole image sequence. Based on this knowledge, several studies have been proposed to exploit the temporal information among the image sequence, which includes using the variation image of the cine images to localize the left ventricle, or using the first order harmonic image of the cine images to localize the left ventricle. These two localization methods may be considered to be similar since the variation image is the sum of the all order harmonic images.

[0007] More may be exploited from the harmonic images. High order harmonic images may also convey information concerning the cardiac dynamic, which is related to the patient's heart function.

[0008] Thus, there is a need to provide a framework for harmonic images assisting diagnosis to address at least the problems above.

Summary

[0009] According to an embodiment, a method for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject is provided. The method may include carrying out a Fourier transformation over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images, and determining, at an identified observation location in the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject.

[0010] According to an embodiment, a device for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject is provided. The device may include a transformation module configured to carry out a Fourier transformation over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images, and a processing module configured to determine, at an identified observation location of the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject.

[0011] According to an embodiment, a computer readable medium is provided. The computer readable medium may have a program recorded thereon, wherein the program, when executed, causes a computer to analyze a sequence of cardiac magnetic resonance (MR) images of a subject. The computer readable medium may include instructions for carrying out a Fourier transformation over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images, and instructions for determining, at an identified observation location of the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject.

Brief Description of the Drawings

[0012] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0013] FIG. 1A shows a flow chart illustrating a method for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject, according to various embodiments.

[0014] FIG. 1B shows a schematic view of a device for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject, according to various embodiments.

[0015] FIG. 1C shows a schematic view of a computer readable medium, according to various embodiments.

[0016] FIG. 2 shows a flowchart illustrating the procedures of a method, according to various embodiments.

[0017] FIG. 3A shows harmonic images at the basal section of a normal subject, where the harmonic images are obtained by a method according to one embodiment.

[0018] FIG. 3B shows corresponding colour harmonic images of FIG. 3A.

5 [0019] FIGS. 4A and 4B show harmonic images of four pairs of normal subjects and patients where the harmonic images are obtained by a method according to one embodiment.

[0020] FIG. 5A shows an exemplary image of high spatial concentration or higher spatial concentration, according to various embodiments.

10 [0021] FIG. 5B shows an exemplary image of low spatial concentration or lower spatial concentration, according to various embodiments.

Detailed Description

15 [0022] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as
20 some embodiments can be combined with one or more other embodiments to form new embodiments.

[0023] Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

25 [0024] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature
30 in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0025] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

5 [0026] In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

[0027] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0028] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

10 [0029] As used herein, the phrase of the form of “at least one of A or B” may include A or B or both A and B. Correspondingly, the phrase of the form of “at least one of A or B or C”, or including further listed items, may include any and all combinations of one or more of the associated listed items.

15 [0030] Various embodiments may provide a system and methods to analyze harmonic images for heart function assessment.

[0031] Various embodiments may provide a method or a computer-aid diagnosis tool for heart function assessment.

20 [0032] Various embodiments may provide an approach to assess a patient’s medical condition directly from the magnetic resonance (MR) images (e.g., cardiac MR images), free of the nondeterministic segmentation step, at least in part motivated by the difficulty of precise and robust automatic chamber segmentation of conventional approaches.

[0033] Various embodiments may provide a framework for the diagnosis of heart function in patients with diverse cardiovascular diseases.

25 [0034] Various embodiments may provide or unveil the relationship between cine MR images and cardiac function. In the current clinical practice, cardiologists and radiologists need to playback the cine image repeatedly to determine the regularity of the cardiac motion, strongly relying on their experiences. More quantitative assessment such as ejection fraction (EF) is only obtainable after the cardiac structure is constructed, which is tedious and time-consuming. The procedure is also subject to high intra/inter-clinician
30 variability. In contrast, various embodiments may enable inspection of the cine MR

images from the spectrum aspect. The procedure of various embodiments is highly automated, deterministic, and efficient.

[0035] Possible applications of the approach of various embodiments may include but not limited to the following: (i) a facilitation for some cardiac MR images processing tasks such as chamber segmentation, image registration; and/or (ii) automatic computer-aided diagnosis method from or based on cine MR images for specific cardiovascular diseases such as cardiac dyssynchrony in heart failure.

[0036] Various embodiments may have some challenges or limitations, for example, in the reliance on a high temporal resolution and a fair image resolution. Spectral analysis and the resulting harmonic image precision are related to both the time interval and the pixel spacing. As such, the approach of various embodiments may be applied to magnetic resonance imaging (MRI). The relatively low temporal resolution of computerized tomography (CT) images and poor echocardiography images are not able to facilitate the computer-aided tool or method of various embodiments.

[0037] Various embodiments may provide a method of distinguishing a patient with a heart disease from a normal subject (e.g., a person that does not a heart disease or a healthy person), the method including computing all harmonic of a Fourier transform over time for each slide or slice of a three-dimensional (3D) image of a heart (or part thereof) of a subject to generate harmonic images to determine scattering and brightness intensity of pixels.

[0038] In various embodiments, more scattering and noisy brightness may indicate that the subject or patient is suffering from a heart disease. For example, the patient may have a heart disease such as myocardial infarction, repaired tetralogy of fallot, or hypertrophic cardiomyopathy.

[0039] In various embodiments, a more concentrated brightness may indicate a normal subject (e.g., free of or without suffering from a heart disease).

[0040] Various embodiments may provide a method of diagnosing a patient with types of heart disease, the method including computing all harmonic of a Fourier transform over time for each slide or slice of a three-dimensional (3D) image of a heart (or part thereof) of a subject to generate harmonic images to determine scattering and brightness intensity of pixels.

[0041] Various embodiments may relate to a computer-aided technique and method for analyzing harmonic images and assessing ventricular deformation from magnetic resonance imaging (MRI). Various embodiments may involve Digital Imaging and Communications in Medicine (DICOM) reader, discrete Fourier transform (DFT), and harmonic images analysis to target one or more regions having abnormal deformation. From the cardiac MRI, Discrete Fourier Transform may be conducted pixel-wise on the image sequence. Harmonic images of all frequencies (e.g., the entire frequency range) may be analyzed visually and quantitatively to determine different patterns of the left and right ventricles of the heart on the spectrum. The first order harmonic images of the normal controls (e.g., normal subjects who may not be suffering from a heart disease) may present a more concentrated brightness around the myocardium of the heart compared to patients suffering from a heart disease. In other words, the patients' first order harmonic images may show more outliers and noises (e.g., irregular scattering of brightness) out of the epicardium regions. The higher order harmonic images may also present this difference between the normal controls and patients to some extent.

[0042] Various embodiments may use harmonic images and such an approach may serve as an automated computer-aided tool for clinicians. Different from the classic diagnosis routine requiring the chamber segmentation and reconstruction, the various embodiments may directly provide a more efficient approach to analyze and assess cardiac function.

[0043] Harmonic image analysis is a valuable clinical indicator for heart function assessment in patients with diverse heart diseases (e.g., myocardial infarction; repaired tetralogy of fallot, hypertrophic cardiomyopathy, and other cardiovascular diseases), including (but not limited to) monitoring ventricular remodeling in patients after heart attack, and/or evaluating the effectiveness of medical/surgical therapy in patients.

[0044] FIG. 1A shows a flow chart 100 illustrating a method for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject, according to various embodiments.

[0045] At 102, a Fourier transformation is carried out over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images.

[0046] At 104, at an identified observation location in the plurality of harmonic images, a spatial concentration of brightness is determined for establishing a cardiac health of the

subject. This may mean that the spatial concentration of brightness at the identified observation location may be determined.

[0047] In various embodiments, a method for or of analyzing a sequence of cardiac magnetic resonance (MR) images of a subject as described above may be provided.

5 [0048] In various embodiments, the Fourier transformation may include discrete Fourier transformation.

[0049] In the context of various embodiments, the sequence of cardiac MR images may mean images at different slices or planes of a 3D image of a heart of the subject and/or images at the same slice or plane of a 3D image of a heart of the subject at different
10 times.

[0050] In various embodiments, a respective harmonic image of the plurality of harmonic images may correspond to a respective cardiac MR image of the sequence of cardiac MR images.

[0051] In various embodiments, at 104, determining, at an identified observation location
15 of the plurality of harmonic images, a spatial concentration of brightness may mean determining, at an identified observation location of each harmonic image of the plurality of harmonic images, a spatial concentration of brightness.

[0052] In various embodiments, at 104, determining, at an identified observation location of the plurality of harmonic images, a spatial concentration of brightness may mean
20 determining a spatial concentration of brightness of pixels at the identified observation location in the plurality of harmonic images or in each harmonic image of the plurality of harmonic images.

[0053] In various embodiments, the identified observation location may be the same in each or all of the plurality of harmonic images.

25 [0054] In various embodiments, the method may further include determining, at the identified observation location in the plurality of harmonic images, an intensity of brightness for establishing the cardiac health of the subject. This may mean determining a spatial concentration or distribution of brightness of pixels at the identified observation location in the plurality of harmonic images or in each harmonic image of the plurality of
30 harmonic images.

[0055] In various embodiments, at 104, the method may include determining scattering and brightness intensity of pixels of the plurality of harmonic images at the identified observation location.

[0056] In various embodiments of the method, the identified observation location may correspond to a region of a heart of the subject, the region including a myocardium of the heart, and at 104, determining a spatial concentration of brightness may include determining the spatial concentration of brightness around the myocardium.

[0057] In various embodiments, at 104, the method may include determining a status of the cardiac health of the subject based on the determined spatial concentration of brightness.

[0058] In various embodiments, a high spatial concentration of brightness at the identified observation location may indicate a normal status of the cardiac health of the subject.

[0059] In various embodiments, the normal status of the cardiac health of the subject may include or may be a regular motion of a myocardium of a heart of the subject.

[0060] In various embodiments, a low spatial concentration of brightness at the identified observation location may indicate that the subject suffers from a heart disease. For example, there may be scattered and/or noisy brightness. The heart disease may include any one of a myocardial infarction, a repaired tetralogy of a fallot, or hypertrophic cardiomyopathy. Other cardiovascular diseases may also be possible.

[0061] A level or degree of spatial concentration may be exemplified based on two synthesized examples as shown in images 500, 502 of FIGs. 5A and 5B. FIG. 5A shows a “high spatial concentration” image or a “higher spatial concentration” image as compared to FIG. 5B, which shows a “low spatial concentration” image or a “lower spatial concentration” image as compared to FIG. 5A. In FIG. 5B, the “lower spatial concentration” image 502 displays scattered and noisy brightness. To quantify the spatial concept, exemplary math tools may be provided as follow.

[0062] The image 500 may be defined as I such that the pixel (x, y) has brightness intensity $I(x, y)$. The visible pixels may be defined as pixels owning the brightness intensity higher than a significant level L . The visible pixels may form a binary image I_L . The number of connect components in I_L may be $|I_L|$. By changing the significant level L ,

the corresponding $|I_L|$ may be obtained. For the above synthesized image I 500 in FIG. 5A, $|I_L|$ may be considered always 1 for all significant level L . In contrast, for synthesized image I 502 in FIG. 5B, $|I_L|$ may be a variety of larger values for different significant level L . The mean of all $|I_L|$ for a significant level interval $L \in (L_1, L_2)$ may quantify an extent of spatial concentration as follow:

$$\text{SpatialConcen} = \frac{1}{L_2 - L_1} \cdot \sum_{L=L_1}^{L_2} |I_L| \quad \text{Equation [A]}$$

[0063] A lower mean of all $|I_L|$ may indicate a higher spatial concentration in image I_L . The computation of such spatial concentration index may be done in the following exemplary Matlab code.

10 [0064] Program Segment A

```
function conIndex = spatialConcenIndex(I, [L1 L2])
conIndex = 0;
for L = L1:L2
    binaryIM = (I>L);
    % label and count the connected component in binaryIM
    [Label, NUM] = bwlabeln(binaryIM);
    conIndex = conIndex + NUM;
end
conIndex = conIndex / round(L2-L1+1);
```

[0065] In various embodiments, the method may further include carrying out Fourier transformations to obtain the plurality of harmonic images for a plurality of harmonic frequencies. The Fourier transformations may be carried out over time of the sequence of cardiac MR images of the subject.

[0066] In various embodiments, the method may further include carrying out Fourier transformations to obtain the plurality of harmonic images for all harmonic frequencies. The Fourier transformations may be carried out over time of the sequence of cardiac MR images of the subject.

20 [0067] In various embodiments, the method may further include extracting harmonic images of a particular (or predetermined) harmonic order from the plurality of harmonic images in determining the spatial concentration of brightness.

[0068] In various embodiments, the method may further include extracting the first order harmonic images from the plurality of harmonic images in determining the spatial concentration of brightness.

[0069] In various embodiments, the method may further include extracting harmonic images of a higher order from the plurality of harmonic images in determining the spatial concentration of brightness. For example, second order, third order, fourth order or any higher order harmonic image may be extracted.

5 [0070] In various embodiments, the method may further include analyzing the plurality of harmonic images to determine observation location patterns in identifying one or more observation locations.

[0071] While the method described above is illustrated and described as a series of steps or events, it will be appreciated that any ordering of such steps or events are not to be interpreted in a limiting sense. For example, some steps may occur in different orders and/or concurrently with other steps or events apart from those illustrated and/or described herein. In addition, not all illustrated steps may be required to implement one or more aspects or embodiments described herein. Also, one or more of the steps depicted herein may be carried out in one or more separate acts and/or phases.

15 [0072] FIG. 1B shows a schematic view of a device 110 for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject, according to various embodiments. The device 110 includes a transformation module 112 configured to carry out a Fourier transformation over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images, and a processing module 114 configured to determine, at an identified observation location of the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject. The line indicated as 120 represents the coupling between the transformation module 112 and the processing module 114, which may include mechanical and/or electrical coupling.

20 [0073] In various embodiments, the processing module 114 may be further configured to, determine, at the identified observation location in the plurality of harmonic images, an intensity of brightness for establishing the cardiac health of the subject.

[0074] In various embodiments, the device 110 may further include a determining module 116 configured to determine a status of the cardiac health of the subject based on the determined spatial concentration of brightness.

30 [0075] In various embodiments, the device 110 may further include at least one module 118 to carry out a method or a method step as described herein. While shown

separately in FIG. 1B, in various embodiments, it should be appreciated that the module 118 may be or may form part of at least one of the transformation module 112, the processing module 114 or the determining module 116.

[0076] In FIG. 1B, the line 120 may also represent the coupling among the transformation module 112, the processing module 114, the determining module 116 and/or the at least one module 118, which may include mechanical and/or electrical coupling

[0077] FIG. 1C shows a schematic view of a computer readable medium 130, according to various embodiments. The computer readable medium 130 may have a program recorded thereon, wherein the program, when executed, causes a computer to analyze a sequence of cardiac magnetic resonance (MR) images of a subject. The computer readable medium 130 may include instructions for carrying out a Fourier transformation over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images, and instructions for determining, at an identified observation location of the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject.

[0078] In various embodiments, the computer readable medium 130 may further include instructions for determining, at the identified observation location in the plurality of harmonic images, an intensity of brightness for establishing the cardiac health of the subject.

[0079] In various embodiments, the computer readable medium 130 may further include instructions for determining a status of the cardiac health of the subject based on the determined spatial concentration of brightness.

[0080] In various embodiments, the computer readable medium 130 may further include instructions to carry out a method or a method step as described herein.

[0081] In the context of various embodiments, the identified observation location may include at least one of a basal portion of a heart, a mid-ventricle portion of a heart, a portion between a basal portion and a mid-ventricle portion of a heart, a left ventricle portion of a heart, a right ventricle portion of a heart, a myocardium portion of a heart or an epicardium portion of a heart.

[0082] Examples of a method for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject may be described as follow.

[0083] A method for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject may include three main steps of image acquisition and processing; discrete Fourier transform and spectral analysis; and interpretation. For example, FIG. 2 shows a flowchart 250 illustrating the procedures of the method where an image (MR image) is firstly obtained at image acquisition 252, and then processed at image processing 254. The image processing 254 may involve image metadata reading 255a and image classification 255b. Following that, discrete Fourier transform 256 may be applied to the processed image and spectral analysis 258 may be applied to the transformed information. The spectral analysis 258 may include frequency separation 259a and harmonic image generation 259b. The analyzed information may then be subject to human interpretation 260 and/or computer-aided interpretation 262.

[0084] The above procedures may be implemented by advanced programming languages including but not limited to Matlab, C/C++, and Python. Several exemplary module implementations in Matlab are described below.

[0085] At the image acquisition 252 and image processing 254, the MR images may be obtained in a clinical practice, which may conform to the Digital Imaging and Communications in Medicine (DICOM) protocol. Meta information of all images may be inspected and recorded. According to the 'SeriesDescription' in the DICOM attribute, the short axis images may be grouped. The short axis images may be images of cross-sections of the left and right ventricles of a subject's heart. Usually, the 'SeriesDescription' field of the short-axis images may contain the text such as "sax" depending on the institution conventions. This classification may, for example, be implemented by the following program segments.

[0086] Program Segment 1

```

list=dir([folderPath,'*.dcm']);
ind=[];
sliceL = [];
seriesD = {};
for i=1:size(list,1)
    info=dicominfo([folderPath,list(i).name]);
    seriesD(i) = {info.SeriesDescription};
end
[seriesD,ia,ic] = unique(seriesD);

```

[0087] As seen in Program Segment 1, variable “*list*” is initialized with a *dir* function which lists the contents of all DICOM image files in the folder denoted as *folderPath*. Other variables “*ind*”, “*sliceL*” and “*seriesD*” may also be initialized. The *dicominfo* function may be used to read the metadata from each of the DICOM image files into variable “*info*”, and the *SeriesDescription* of *info* may be consolidated into a location *i* of an array *seriesD*. This may be repeated for the entire content in “*list*”. Thereafter, a *unique* function may be applied on the dataset *seriesD* to return the same values as in *seriesD* but with no repetitions, along with index vectors *ia* and *ic*.

10 [0088] Program Segment 2

```

list=dir([folderPath,'*.dcm']);
flag = [];
for i=1:size(list,1)
    info=dicominfo([folderPath,list(i).name]);
    seriesD(i) = {info.SeriesDescription};
    if( strcmp( info.SeriesDescription , 'tf2d_sax_Ventricular Volume'))
        flag = [flag;i];
    end
end
list = list(flag);

```

[0089] As seen in Program Segment 2, variable “*list*” is initialized with a *dir* function which lists the contents of all DICOM image files in the folder denoted as *folderPath*. Variable “*flag*” may also be initialized. The *dicominfo* function may be used to read the

metadata from each of the DICOM image files into variable “*info*”, and the *SeriesDescription* of *info* may be consolidated into a location *i* of an array *seriesD*. A string comparison may be made between *info.SeriesDescription* and the phrase ‘*tf2d_sax_Ventricular Volume*’. If a match for the string comparison is found, an array
5 *flag* may record the location *i*. This may be repeated for the entire content in “*list*”. Thereafter, variable “*list*” may be updated with the contents of DICOM image files that contain the phrase ‘*tf2d_sax_Ventricular Volume*’. As such, the classification of short axis images containing the text ‘*tf2d_sax_Ventricular Volume*’ may be performed.

[0090] The “ImagePositionPatient” and “InstanceNumber” attributes may be inspected
10 for all short axis images. All short axis images may be re-organized as image-time sequences at multiple slice locations. A typical image sequence at the same slice location may contain about 20 to about 25 images covering a cardiac cycle. A cine MR study may contain about 12 to about 15 slice locations. This data re-organization procedure may, for example, be implemented by the following program segment.

15 [0091] Program Segment 3

```

loc = [];
frameNum = [];
for i=1:size(list,1)
    info=dicominfo([folderPath,list(i).name]);
    loc = [loc;info.SliceLocation];
    frameNum = [frameNum;info.InstanceNumber];
end
loc = unique(loc);
[M,N] = size(dicomread([folderPath,list(1).name]]));
L = size(loc,1);
T = max(frameNum);
fullData = repmat(0,[M,N,L,T]);
posData = repmat([0 0 0],[L,1]);
for ii=1:size(loc,1)
    for i=1:size(list,1)
        temp=list(i).name;
        info=dicominfo([folderPath,temp]);
        if( (info.SliceLocation) == loc(ii))
            c=dicomread([folderPath,temp]);
            frame = info.InstanceNumber-1;
            fullData(:, :,ii,frame+1) = c;
            sNo(ii,frame+1) = i;
            posData(ii,:) = info.ImagePositionPatient;
            continue;
        end
    end
end
end

```

[0092] As seen in Program Segment 3, variables “loc” and “frameNum” may be initialized. The *dicominfo* function may be used to read the metadata from each of the classified DICOM image files (for example, as described in Program Segment 2) into variable “info”, and the *SliceLocation* of *info* may be stored in the array *loc*, while the *InstanceNumber* of *info* may be stored in the array *frameNum*. This may be repeated for the entire content in the updated “list” (of Program Segment 2). Thereafter, a *unique* function may be applied on the dataset *loc* to return the same values as in *loc* but with no repetitions. The spatial sizes *M* and *N* may be obtained, and the size of the dataset *loc*

may be denoted as L . The maximum *frameNum* may be denoted as T . A M -by- N -by- L -by- T matrix *fullData* may be created and initialized as "0". A L -by-3 matrix *posData* may be created and initialized as "0". For the entire content in the updated list and for the dataset *loc*, the *dicominfo* function may be used to read the metadata from each of the relevant DICOM image files into variable "*info*" and then, a comparison may be made between the *SliceLocation* of *info* and a particular data in the dataset *loc*. If the values are the same, the respective elements in the matrices *fullData* and *posData* may be updated. As such, the above steps may be repeated for the entire content in the updated list and for the dataset *loc* to form image-time sequences at multiple slice locations.

[0093] At the discrete Fourier transformation 256 and the spectral analysis 258, a spatio-temporal (2D+t) cine Magnetic Resonance (MR) image u with the resolution of $M \times N \times T$ may be given. In other words, the (2D+t) cine MR image may refer to a 2-dimensional image which changes over time, e.g., like a movie. Each pixel position over time presents a discrete time series, (i.e. $u(m, n, t)$, $0 \leq m \leq M-1$, $0 \leq n \leq N-1$, $t = 0, 1, \dots, T-1$). For the rest of the discussion in this section, the spatial coordinates m, n are omitted and are not described for simplicity purposes (e.g., $u(t)$, $t = 0, 1, \dots, T-1$).

[0094] Discrete Fourier transform (DFT) of $u(t)$ may be as follows:

$$U(k) = \sum_{t=0}^{T-1} u(t) e^{-j2\pi(\frac{k}{T})t}, \quad k = 0, \dots, T-1 \quad \text{Equation [1]}$$

[0095] $U(k)$, $k = 0, 1, \dots, T-1$ presents the decomposition of the time sequence $u(t)$ in term of frequency. The k -th harmonic series of u may be defined as inverse discrete Fourier transform (IDFT) to the k -th frequency component separately as follows:

$$u_k(t) = \frac{1}{T} U(k) e^{j2\pi(\frac{k}{T})t}, \quad t = 0, \dots, T-1, k = 0, \dots, T-1 \quad \text{Equation [2]}$$

[0096] The k -th harmonic image may be defined as the L^2 -norm of the k -th harmonic series.

$$\bar{u}_k = \frac{1}{T} \sum_{t=0}^{T-1} |u_k(t)|^2 \quad \text{Equation [3]}$$

[0097]. This spectral transform and harmonic image generation may, for example, be implemented by the following program segment.

[0098] Program Segment 4

```

[M,N,L,T] = size(fullData);
F = fft(fullData,[],4);
H = zeros(M,N,L,T);
for jj = 1:T
    temp = zeros(M,N,L,T);
    temp(:,:,jj) = F(:,:,jj);
    tempH = ifft(temp,[],4);
    H(:,:,jj) = 1/T*sum( (tempH).^2,4);
end

```

[0099] As seen in Program Segment 4, a fast Fourier transformation using a *fft* function may be applied on *fullData* to perform the calculations of Equation [1]. An inverse fast Fourier transformation using a *ifft* function may then be applied to perform the calculations of Equation [2]. An array *H* may be updated with the L^2 -norm of the k -th harmonic series of Equation [3], which contains harmonic images of all orders.

[0100] Examples of several harmonic images at the basal section of a normal volunteer subject are shown in the gray images 350a, 352a, 354a, 356a of FIG. 3A and the corresponding colour images 350b, 352b, 354b, 356b of FIG. 3B. The harmonic images 350a, 352a, 354a, 356a are of the same size. A scale bar in arbitrary units is provided for respective FIGS. 3A and 3B, indicating the intensities of brightness. As observed in FIG. 3A, the spatial concentrations of brightness in each of the harmonic images 350a, 352a, 354a, 356a are considerably similar to one another but the intensities of brightness may differ. For example, the harmonic image 350a may be seen to have the highest intensity of brightness as compared to the harmonic images 352a, 354a, 356a. The harmonic image 350a may be a low order harmonic image (e.g., the first harmonic image), while the harmonic images 352a, 354a, 356a may be of higher orders.

[0101] To determine a health status, more specifically, a cardiac health status of a patient, interpretation of harmonic images of the patient's heart may be carried out in comparison to the harmonic images of a normal subject's heart.

[0102] FIGS. 4A and 4B present a side-by-side comparison between the same order harmonic images of four pairs of normal subjects versus patients at the multiple slice locations (the locations being selected between basal and mid-ventricle). In other words,

for example, the harmonic images 450a, 450b, 450c, 450d of Normal Subject A may be correspondingly compared against the same order harmonic images 460a, 460b, 460c, 460d of Patient A. The harmonic images 452a, 452b, 452c, 452d of Normal Subject B may be correspondingly compared against the same order harmonic images 462a, 462b, 462c, 462d of Patient B. The harmonic images 454a, 454b, 454c, 454d of Normal Subject C may be correspondingly compared against the same order harmonic images 464a, 464b, 464c, 464d of Patient C. The harmonic images 456a, 456b, 456c, 456d of Normal Subject D may be correspondingly compared against the same order harmonic images 466a, 466b, 466c, 466d of Patient D. The harmonic images of each of the normal subjects and each of the patients are of the same size. A scale bar in arbitrary units is provided for respective FIGs. 4A and 4B, indicating the intensities of brightness.

[0103] It may be observed that the harmonic images of the normal subjects present a more concentrated brightness (spatially) around the myocardium. In the contrast, the patient's harmonic images have more scattered and noisy brightness.

[0104] These differences between normal subjects and patients may be used for diagnosis purpose. The more noisy and scattered brightness on the harmonic images may imply a more irregular motion of the myocardium. The interpretation of a harmonic image may be performed by either human interpretation or computer-aided interpretation or both.

[0105] Various embodiments may be used or employed in at least one of the following applications: (i) image registration to minimize the patient's motion; (ii) (heart) chamber segmentation; (iii) three-dimensional (3D) (heart) chamber reconstructions; (iv) cardiac surface geometric analysis; or (v) classification of normal subjects and patients (e.g., subjects with a heart disease).

[0106] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A method for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject, the method comprising:

5 carrying out a Fourier transformation over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images; and

determining, at an identified observation location in the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject.

10 2. The method as claimed in claim 1, further comprising, determining, at the identified observation location in the plurality of harmonic images, an intensity of brightness for establishing the cardiac health of the subject.

15 3. The method as claimed in claim 1, wherein determining a spatial concentration of brightness comprises determining scattering and brightness intensity of pixels of the plurality of harmonic images at the identified observation location.

4. The method as claimed in any one of claims 1 to 3,
20 wherein the identified observation location corresponds to a region of a heart of the subject, the region comprising a myocardium of the heart, and
wherein determining a spatial concentration of brightness comprises determining the spatial concentration of brightness around the myocardium.

25 5. The method as claimed in any one of claims 1 to 4, further comprising determining a status of the cardiac health of the subject based on the determined spatial concentration of brightness.

6. The method as claimed in claim 5, wherein a high spatial concentration of
30 brightness at the identified observation location indicates a normal status of the cardiac health of the subject.

7. The method as claimed in claim 5, wherein a low spatial concentration of brightness at the identified observation location indicates that the subject suffers from a heart disease.

8. The method as claimed in claim 7, wherein the heart disease is any one of a myocardial infarction, a repaired tetralogy of a Fallot, or hypertrophic cardiomyopathy.

9. The method as claimed in claim 6, wherein the normal status of the cardiac health of the subject is a regular motion of a myocardium of a heart of the subject.

10. The method as claimed in any one of claims 1 to 9, further comprising carrying out Fourier transformations to obtain the plurality of harmonic images for a plurality of harmonic frequencies.

11. The method as claimed in any one of claims 1 to 10, further comprising carrying out Fourier transformations to obtain the plurality of harmonic images for all harmonic frequencies.

12. The method as claimed in any one of claims 1 to 11, further comprising extracting harmonic images of a particular harmonic order from the plurality of harmonic images in determining the spatial concentration of brightness.

13. The method as claimed in any one of claims 1 to 12, further comprising extracting the first order harmonic images from the plurality of harmonic images in determining the spatial concentration of brightness.

14. The method as claimed in claim 13, further comprising extracting harmonic images of a higher order from the plurality of harmonic images in determining the spatial concentration of brightness.

15. The method as claimed in any one of claims 1 to 14, wherein the identified observation location comprises at least one of a basal portion of a heart, a mid-ventricle portion of a heart, a portion between a basal portion and a mid-ventricle portion of a heart, a left ventricle portion of a heart, a right ventricle portion of a heart, a myocardium portion of a heart or an epicardium portion of a heart.

16. The method as claimed in any one of claims 1 to 15, further comprising analyzing the plurality of harmonic images to determine observation location patterns in identifying one or more observation locations.

17. A device for analyzing a sequence of cardiac magnetic resonance (MR) images of a subject, the device comprising:

a transformation module configured to carry out a Fourier transformation over time of the sequence of cardiac MR images of the subject to obtain a plurality of harmonic images; and

a processing module configured to determine, at an identified observation location of the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject.

18. The device as claimed in claim 17, wherein the processing module is further configured to, determine, at the identified observation location in the plurality of harmonic images, an intensity of brightness for establishing the cardiac health of the subject.

19. The device as claimed in claim 17 or 18, further comprising a determining module configured to determine a status of the cardiac health of the subject based on the determined spatial concentration of brightness.

20. The device as claimed in claim 19, comprising at least one module to carry out a method as claimed in any one of claims 2 to 16.

21. A computer readable medium having a program recorded thereon, wherein the program, when executed, causes a computer to analyze a sequence of cardiac magnetic resonance (MR) images of a subject, the computer readable medium comprising:

instructions for carrying out a Fourier transformation over time of the sequence of
5 cardiac MR images of the subject to obtain a plurality of harmonic images; and

instructions for determining, at an identified observation location of the plurality of harmonic images, a spatial concentration of brightness for establishing a cardiac health of the subject.

10 22. The computer readable medium as claimed in claim 21, further comprising instructions for determining, at the identified observation location in the plurality of harmonic images, an intensity of brightness for establishing the cardiac health of the subject.

15 23. The computer readable medium as claimed in claim 21 or 22, further comprising instructions for determining a status of the cardiac health of the subject based on the determined spatial concentration of brightness.

20 24. The computer readable medium as claimed in claim 23, further comprising instructions to carry out a method as claimed in any one of claims 2 to 16.

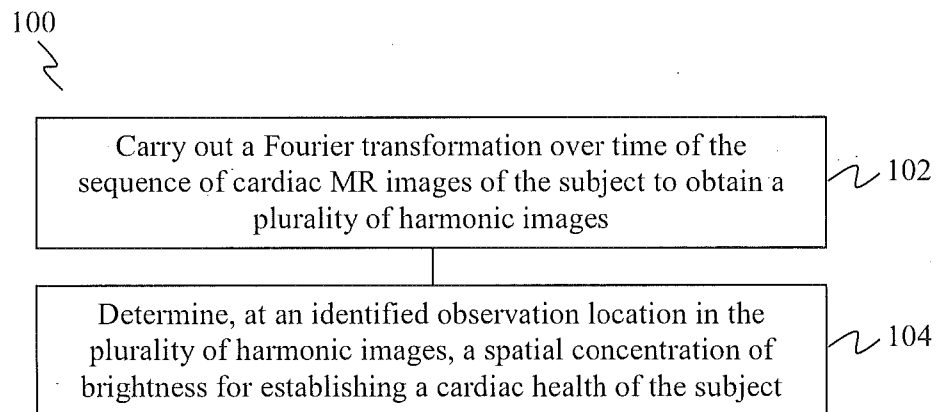


FIG. 1A

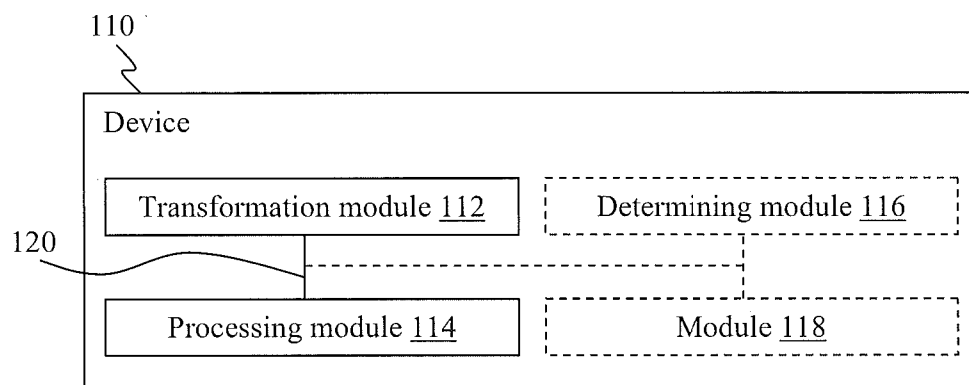


FIG. 1B

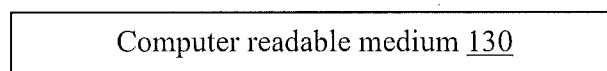


FIG. 1C

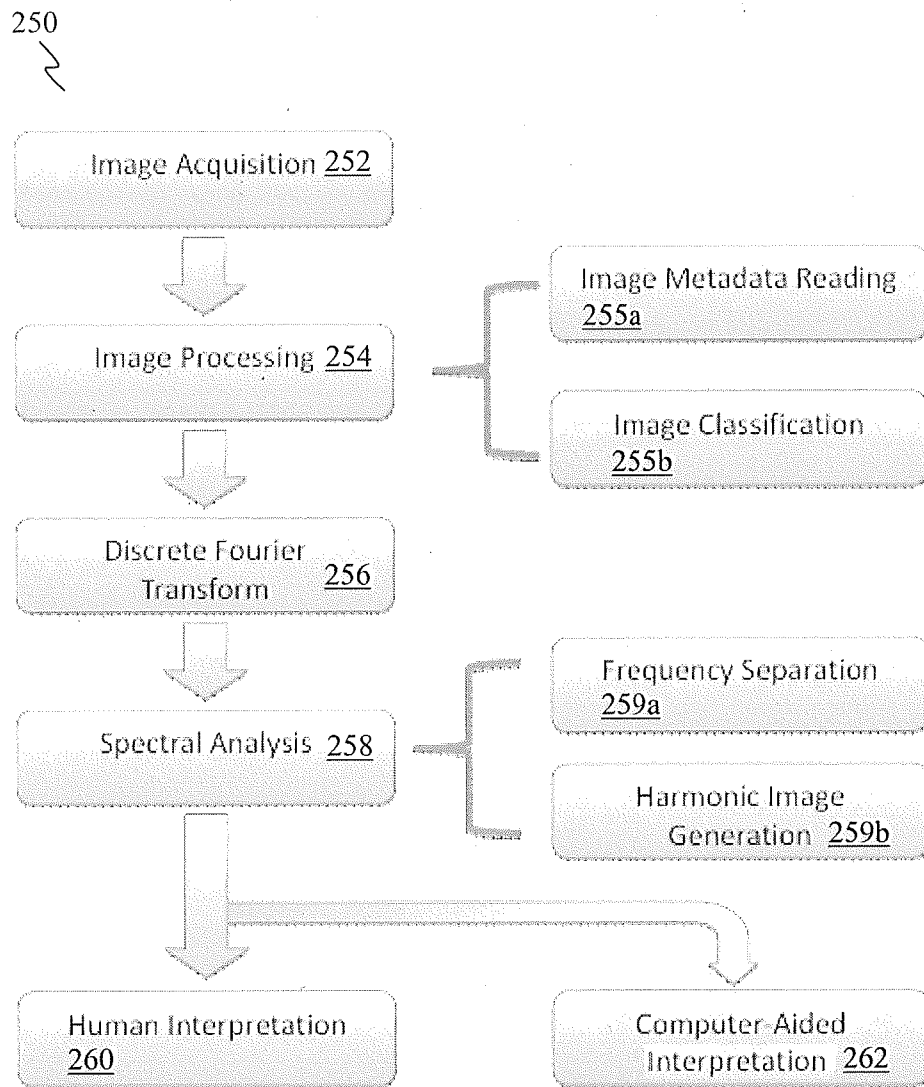


FIG. 2

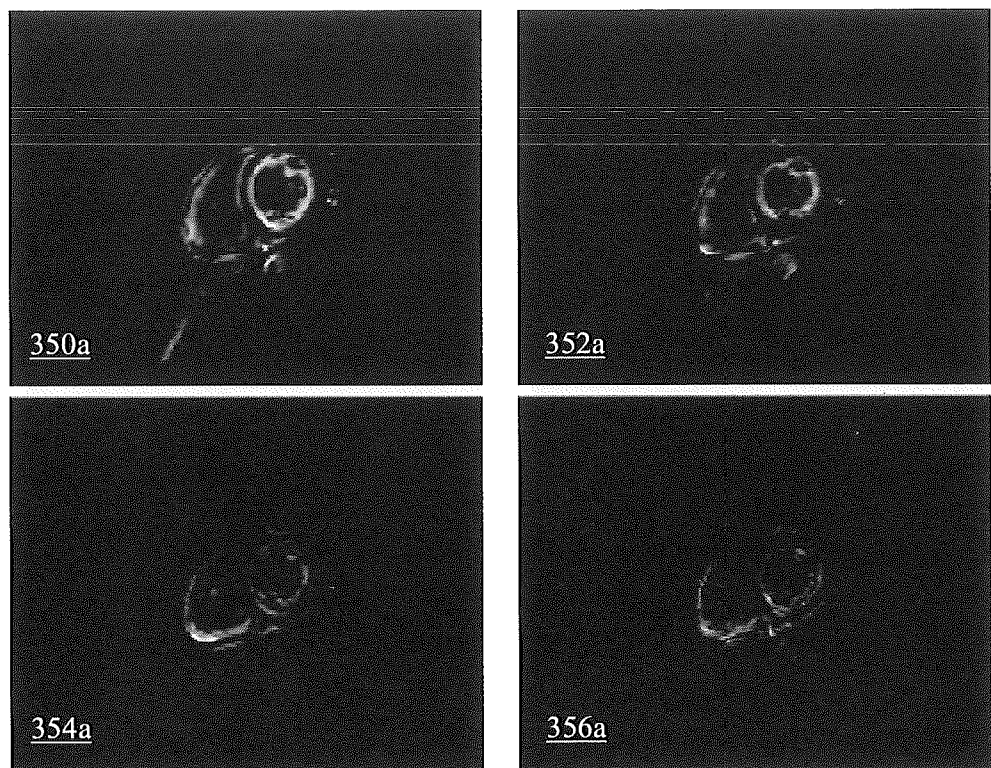


FIG. 3A

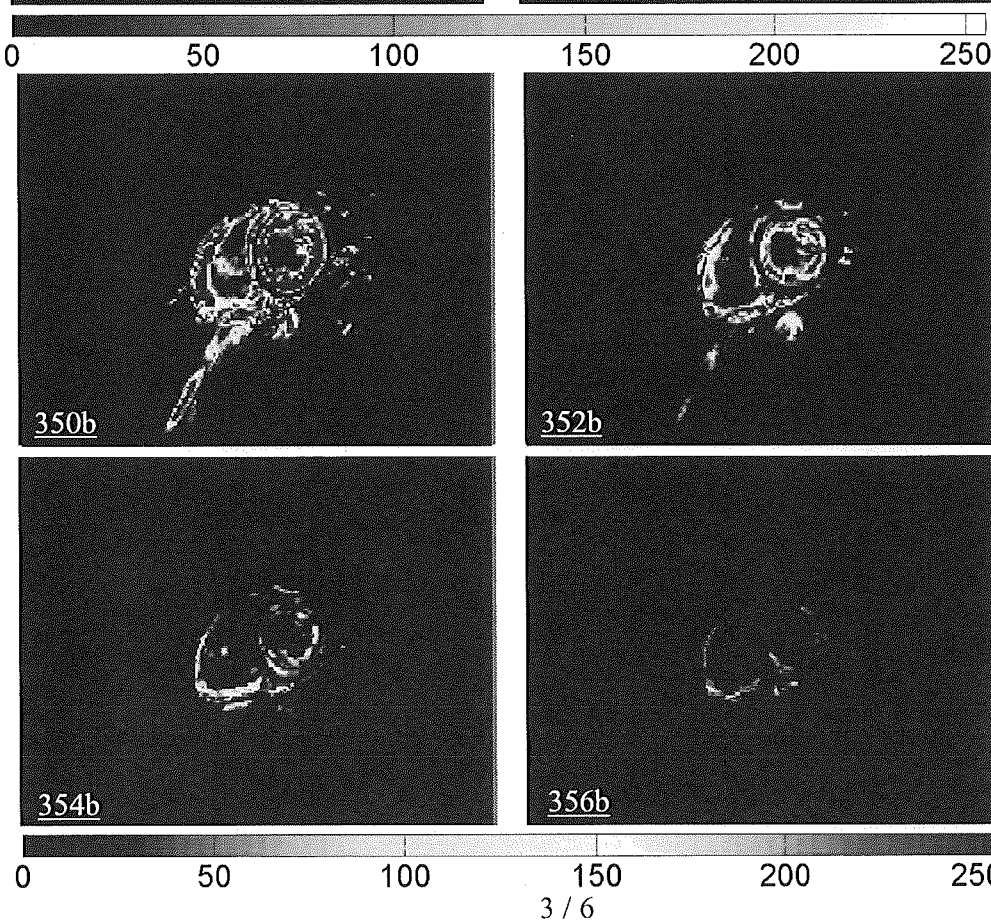


FIG. 3B

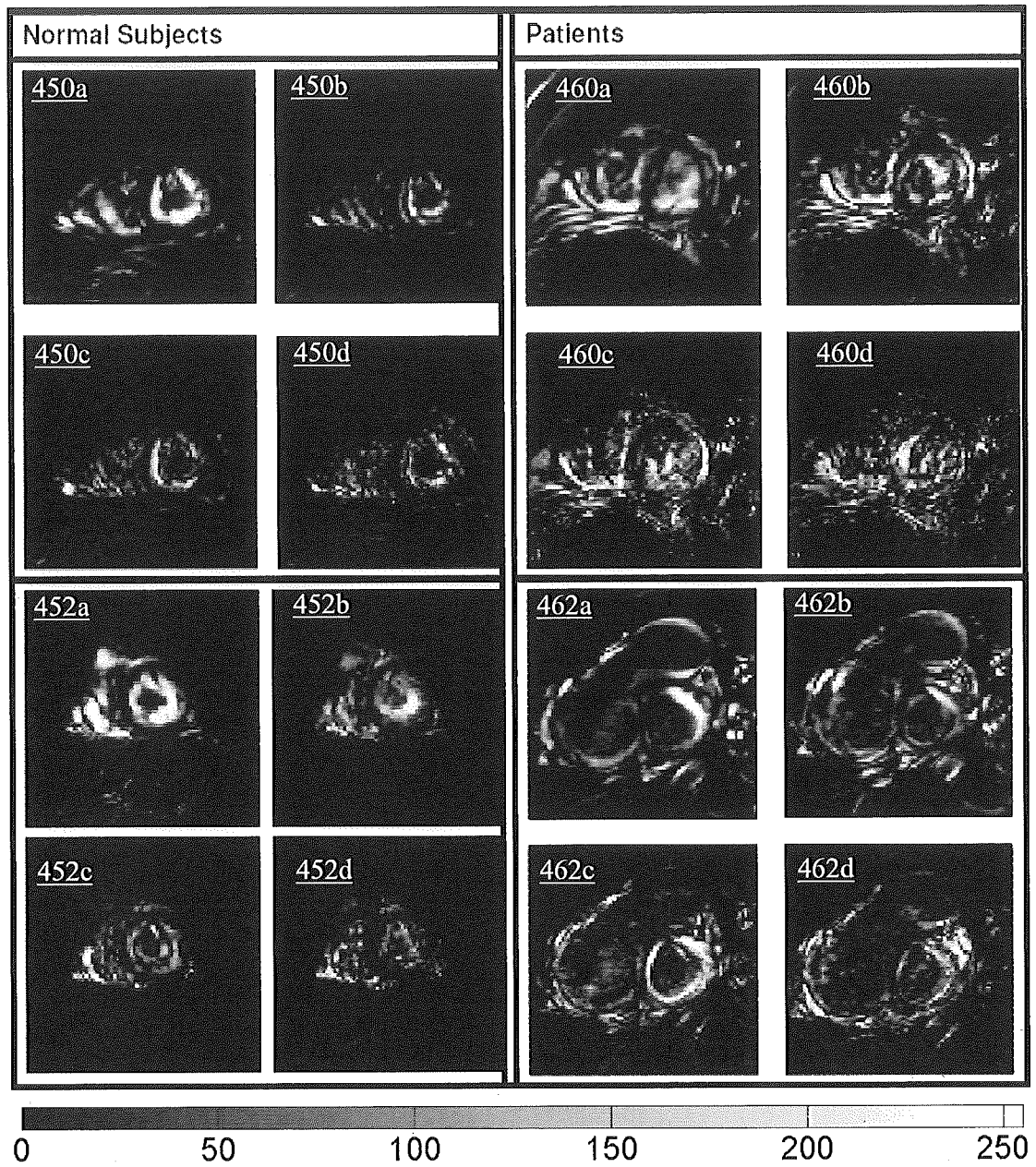


FIG. 4A

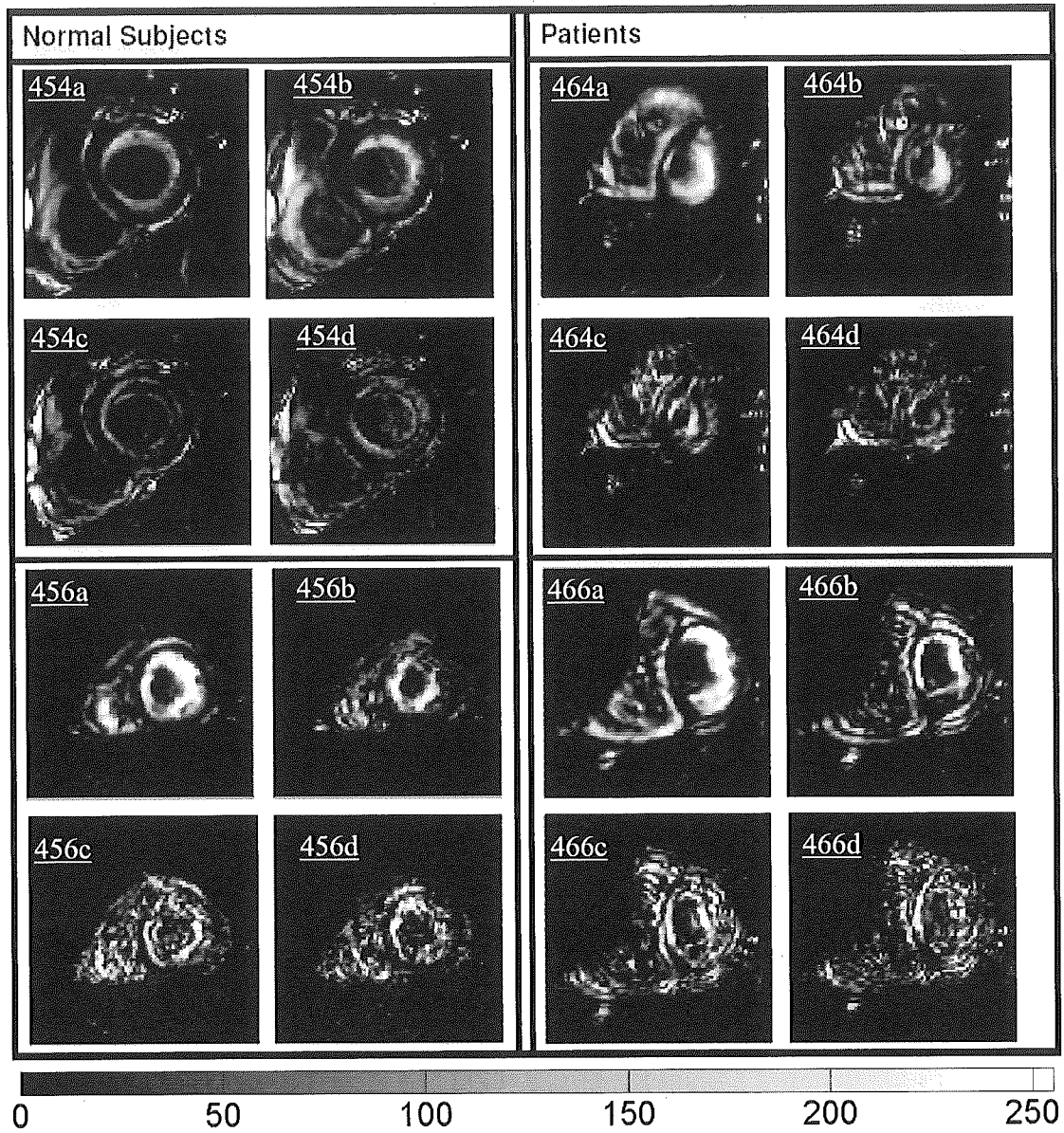


FIG. 4B

500 ↗

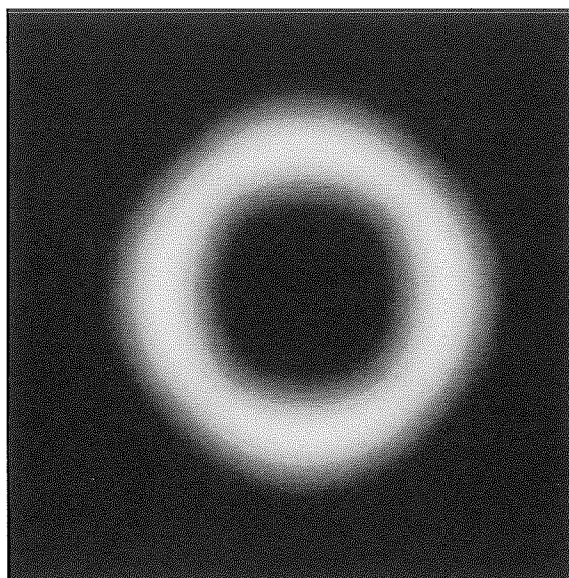


FIG. 5A

502 ↗

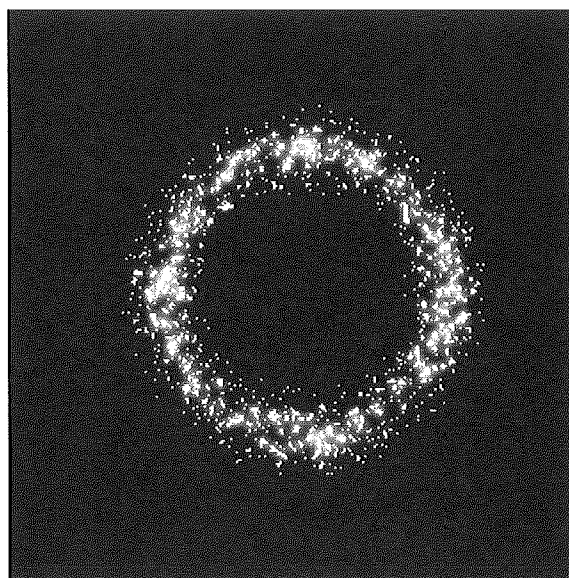


FIG. 5B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2015/000115

A. CLASSIFICATION OF SUBJECT MATTER

A61B 5/055 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Database: EPODOC, WPIAP. Cluster: TXTE. IPC: A61B5/00 CPC: A61B2576/023, A61B5/0044, A61B5/055, A61B6/503, G06T2207/30048, G06T2207/10088, A61B5/7257. Keywords: Cardiac, heart, Fourier, transform, harmonic, magnetic resonance, MR, MRI, CMR and similar terms. Applicant and inventor name search in EPODOC and WPIAP. Applicant and inventor name searched in internal databases provided by IP Australia.

GOOGLE, GOOGLE PATENTS, GOOGLE SCHOLAR, PUBMED. Keywords: cardiac, heart, cine, MR images, segmentation, left ventricle, Fourier transform, harmonics and similar terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

☒ Further documents are listed in the continuation of Box C☒ See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		
Date of the actual completion of the international search 24 June 2015		Date of mailing of the international search report 24 June 2015	
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au		Authorised officer Xin-Lin Goh AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262837991	

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/SG2015/000115
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	LIN X., et al. "Automated detection of left ventricle in 4D MR images: experience from a large study". 9th International Conference on Medical Image Computing and Computer-Assisted Intervention, Copenhagen, Denmark, October 1-6, 2006, Proceedings, Part I, pages 728-735. See Abstract, Section 1 Introduction on page 728, Section 2 Method on page 730, Section 2.2 Fourier Transform and Section 2.3 Fast ROI Analysis over time on page 731, Section 3 Results on page 733 and Figures 2a, 2c, 2d, 2e and 3.	1 to 24
A	PETITJEAN, C., et al. "A review of segmentation methods in short axis cardiac MR images". Medical Image Analysis, 2011, Volume 15, Issue 2, pages 169-184. See whole document	
A	US 2009/0093707 A1 (MAIER) 09 April 2009 See whole document	

Form PCT/ISA/210 (fifth sheet) (July 2009)

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/SG2015/000115	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 2009/0093707 A1	09 April 2009	US 8583209 B2	12 Nov 2013
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2009)			