Cell Music: The Sonification of Digitalized Fast-Fourier Transformed Microscopic Images

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Abstract. A new way for extracting sound from images is described using the bidimensional Fast Fourier Transform (FFT) of digitalized microscopic images of human cells. The FFT images provide information on the presence of cyclic harmonic structures inherent in the texture of the original image, since each pixel of the FFT image defines a frequency and an amplitude. Reading the FFT image by a pointer rotating in a clockwise manner, it is possible to transform this information into a sound equivalent to the original image. This method is illustrated with images from cells of benign and malignant human neoplastic tissue, which can be differentiated by their equivalent "cell sound".

1. Introduction

The search for an interface between art and science is very old. Theories associating music with the cyclic motions of planets have been proclaimed in ancient times for instance by Plato , Boethius, Ptolemy or Pythagoras. Later, the astronomer Kepler [KEPLER, 1619] compared the planets' velocities to musical chords and thus elaborated a theory of the harmonic musical structure of the planetary system. However, only at the beginning of the 19th century, the french scientist J. B. Fourier described mathematically the harmonic de-composition, demonstrating that any "irregular" continuous function could be interpreted as a sum of sine and cosine waves. This "Fourier Transformation" has been widely used for the analysis and treatment of communication signals but can also be applied for the description of images, since regularly organized relations between picture elements may be interpreted as cyclic, harmonic events. The Fourier transformation describes exactly the spacial direction, frequency and intensity of these cyclic events by harmonic func-tions. This may be compared to bidimensional plane waveforms similar to waves on the surface of a lake.

The analysis of images and specially of microscopic images is very important in medicine because it is one of the main fundamentals of diagnosis. Cells of diseased human tissues obtained by brushing, aspiration or biopsy are fixed, (in case of biopsies embedded and cut), mounted on glass slides, stained, and finally analyzed by microscopy. The experienced examinator identifies under the microscope the different cell types and

* Financiado pela FAPESP processo 99/11947-0

pathologic alterations of cells or tissues by their characteristic microscopic features, thus elaborating a diagnosis. The texure of the arrangement of DNA and proteins of the cell nucleus, called chromatin, is very important for the recognition of the cell type. Alterations of the genome, as they occur in malignant tumours provoke modifications of the chromatin texture, which can be recognized by microscopic examination. Unfortunately there is some variation in diagnosis even between experienced observers. Therefore, image analysis techniques with the help of computers have been recently introduced for the examination of microscopic images in order to get more reliable information independently of inter- or intraobserver variability. For this purpose, microscopic images of cells are digitalized and stored electronically. Then they are studied with the help of computer algorithms, according to their topologial features, their matrix features or according to mathematical function theory. One of the posssibilities is to extract mathematical descriptors from Fourier transfomed images [GONZALEZ and WOODS, 1987] that are able to characterize precisely different cell types. Since this procedure highlights the harmonic structure of the images, we tried to find out whether it would be possible to create sound from Fourier transformed microscopic images, and to find out whether this sound could be equivalent to inherent structures which are of diagnostic relevance. In other words, we looked whether different cell types or diseases can be characterized by their "cell sound".

2. Material and Methods

The source of our images were routine hematoxylin-eosin stained cytologic preparations from brush preparations of patients with bronchial diseases. Microscopic images at 100x objective magnification were captured with a commercial image analysis system (KS 300 Zeiss, Kontron) and stored in bitmap format. Levels of luminance for each colour ranged between 0 (absence of light) and 255 (very bright). For each pixel the mean gray value was calculated. Since we were interested to examine individual nuclei we had to separate them from the background by segmentation (figure 1).

The Fast Fourier Transform (FFT) image was obtained by the formula:

$$F(u, v) = \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} I(x, y) e^{\frac{j2\pi(ux + vy)}{N}} \qquad (1)$$

To obtain useful information in order to create sound, we choosed the moment of inertia, because it represents the amplitude of the sinus wave. Figures 1c and 1d show the transformed images.

Each pixel in the transformed image represents a harmonic function in the original space. The sum of all pixels of the transformed image represents the sum of the corresponding harmonic functions in the spatial domain. An important property of this transformed image is the symmetry with respect to the central point with two identical halves, one of them rotated 180 degrees. In the FFT image the distance of a pixel to the center of the image represents the frequency and its luminance corresponds to the amplitude of the harmonic function .The direction of the vector between the pixel and the center is identical to the direction of the wave in the original image.

The following properties of the FFT image are important for the creation of sound: The distance of each pixel from the central point represents its spatial frequency, with a

$$f_{u,v} = 64\sqrt{u^2 + v^2}$$

minimal distance of 1 pixel. Since the limit of human accustic frequency perception is about 20 Hz, we defined that the nearest point of the transformed image should be equivalent to a sound of 64 Hz. Thus, we created the following mathematical rule for the calculation of the frequency of each pixel:

(2)

Due to the scaling theorem, the modules of each pixel of the transformed image become smaller with increasing distance to the centre, i.e increasing frequency. Therefore it is necessary to multiply the module by the distance to the centre to obtain the amplitude, in order to correct this distortion.

$$A_{u,v} = |F(u,v)|\sqrt{u^2+v^2} \tag{3}$$

In that way every pixel in the FFT image represents a sound with defined frequency and amplitude. Music has a time dimension and therefore it is necessary to introduce rules for a time sequence, which defines the reading of the pixels in the FFT image. We introduced the following rule: a vector, like a pointer on a clock, is moving clockwise in 30 seconds from the zero hour to the six hour position. The sound equivalent to each pixel is played when the vector strikes the pixel . In other words, the time sequence is defined by the angle between the vertical line and the spatial direction of each pixel F(u,v).

$$t_{0_{u,v}} = \frac{30\arctan(\frac{v}{u})}{\pi} + 15 \tag{4}$$

We also defined in the equation 4 that the sound duration would be inversely proportional to the frequency, that is, low frequency sounds would have greater durations. This was necessary because of the different velocities comparing high and low frequency ranges.

$$E_{u,v}(t - t_{0_{u,v}}) = \frac{-(t - t_{0_{u,v}})f_{u,v}}{64} + 1 \tag{5}$$

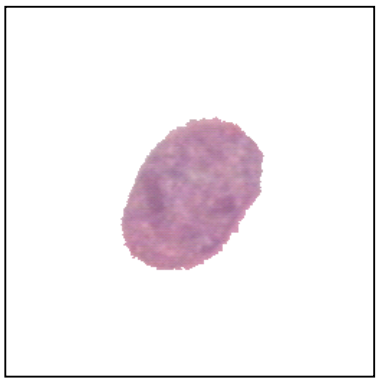
Using these rules, it is possible to express sounds equivalent to the information inherent in the texture of an microscopic image .

$$x_{u,v}(t) = A_{u,v}E_{u,v}(t - t_{0_{u,v}})\sin(2\pi(t - t_{0_{u,v}})f_{u,v}) \tag{6}$$

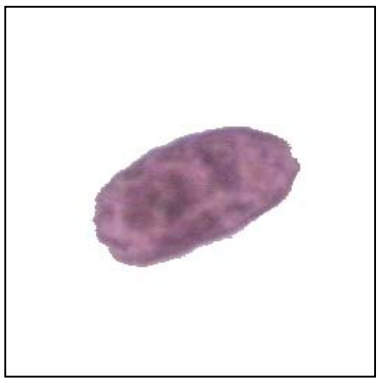
Finally, we can obtain the sound wave O(t) express by

$$O(t) = \sum\sum x_{u,v}(t - t_{0_{u,v}}) \tag{7}$$

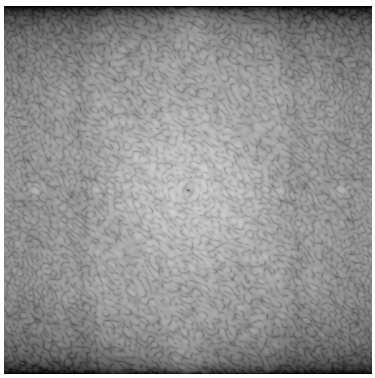
The software used was developed in our own laboratories (INPI registration number 42232).



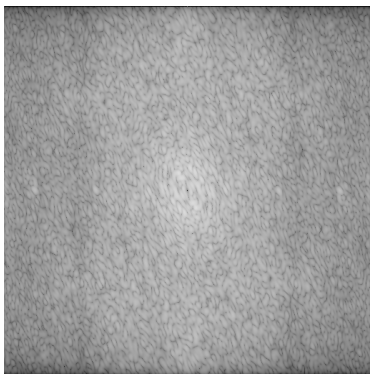
a) Chromatin texture of a normal epithelial cell of bronchial mucosa.



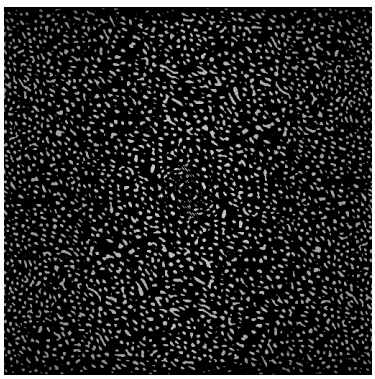
b) Chromatin texture of a malignant neoplastic cell (adenocarcinoma)



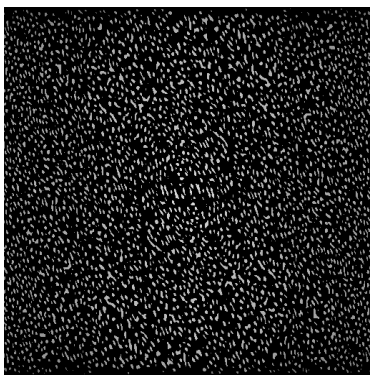
c) FFT image of image a (normal cell)



d) FFT image of b (adenocarcinoma)



e) Domes (clusters) of the FFT image of the normal cell a



f) Domes (clusters) of the FFT image of the adenocarcinoma cell b.

Figure 1: Comparison of two different cell types.

3. Results

The sound created by the above mentioned algorithm is a mixture of different frequencies and specially rich in low frequencies, reminding of machine sound and not very useful for acoustic analysis. Therefore we filtered out the most important frequencies by geodesic reconstruction [VINCENT, 1993]. This method defines subregions in the FFT image

around regional maxima with a luminance difference up to three gray levels lower (figures 1e and 1f).

Only pixels within domes of gray level values in the FFT image contributed to the generation of sound . The results were aesthetically more satifactory and permitted differentiation of different cell types. (wavefile normal) and (wavefile cancer). Since in the malignant cells usually predominate lower frequencies, these can be easily recognized in the cell sound as slowly moving chords of lower frequencies with intense amplitudes (wavefile cancer).

4. Discussion

The use of images as a sound source is not new, as Delator (2000) has shown in his interesting review. In histopatology and cytopathology however, we are not aware of any similar investigation on sonification for analysis of microscopic images. The following applications are possible:

- Audio identification of different cell types by applying an efficient sound coding similar to that propsed by Delatour for identification of molecules. This would result in creation of "typical" sounds equivalent to certain cell types, which we would like to call "equivalent sounds", a kind of "fingerprint" for the chromatin pattern in cell nuclei. This is possible because we use a sound translation by a fixed scale transformation and do not use arbitrary sounds or triggering. Therefore our results are highly reproductible.

- A synesthetic way to understand microscopic structures , since the auditory system can be used for pattern recognition [LUNNEY and MORRISON, 1990] and [DELATOUR, 2000]. Image analysis is nowadays used for diagnosis and may give some prognostic information [CIA et al., 1999, METZE and LORAND-METZE, 1999, METZE et al., 2000]. In order to make an "exact" diagnosis, the use of algorithms based on variables derived by texture analysis is necessary [CIA et al., 1999]. The sonification of chromatin structures may contribute to an intuitive comprehension of texture analysis, which usually is difficult to be understood. Even visually impaired person may benefit from the sonification of the chromatin texture. In that way, it may contribute to the monitoring or comprehension of biological structure.

- Although the computer algorithm proposed by us is a precise "translation" of optical texture to an acoustical one, by strictly defined signal processing rules, the possibilities to use different time scales or frequency scales, octave transpositions etc. opens large possibilities for personal artistic expression. Moreover the sound generated could be used for interactive computer music with a performer reacting to in an improvisational sense.

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