SPECKLE STUDY TO BIOMEDICAL APPLICATIONS

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Abstract: Speckle is an interference phenomenon which appears when a coherent light interacts with a scattering medium. Various scatters in the media correspond to secondaries sources of partials waves which will interfere and occurs consequently a speckle pattern. The interaction light/medium provides informations on the optical properties of the medium. For this reason, we were interested by biomedical applications of the speckle statistical study, particularly in dermatological applications. One first objective is to discriminate healthy skin from pathology skin. The objective of these next years is to set up, on one hand, a bond between statistical parameters from speckle patterns and opticals properties of the medium, and, on the other hand, a bond between optical properties and biological properties of the scattering medium. This article presents the first results above the statistical study of speckle according to a stochastic approach based on Brownian motion theory applied to dermatologic pathologies. This approach already allowed to discriminate several medium.

Introduction

When a laser illuminates a heterogeneous medium, we can see a luminous swarming around it: they are grains of speckle. Such a medium presents local variations of density and thus of refraction index. These local zones constitute diffusers which are randomly distributed in the medium. The partial waves coming from these secondary sources will interfere and produce then a figure with the granular aspect, called speckle, in which there are spots more or less luminous. It is enough to place a photographic plate at any distance of the object to record the speckle. Figure 1 shows a speckle pattern produced by the laser illumination on a scattering medium. For a long time, it was considered as a simple noise in imaging, the objective was to suppress it. However, speckle is a phenomenon which directly rises from the interaction light/medium, the speckle contains informations about properties of the medium and in particular about optical properties. This is the reason why, since few years, physician took an interest in the exploitation of this speckle and several applications have been developed: in stellar physics, in industry with the study of rugosity and deformation of object, or also in medical imagery, domain which particularly concerns us.

Goodman and Goldfisher [1-2] were the first to study the statistical properties of the speckle by using the power spectral density and its auto-correlation function. The statistic of the first and second order allows applications in imaging, as the determination of the contrast [3]. Many researchers have also explored the relationships between the speckle dimensions and the experimental conditions [4-6]. Speckle is time variant when the scattering medium is dynamic, therefore, this classical frequential approach is not sufficient to explain a non-stationary phenomenon. An original approach of the speckle was then introduced recently into which a parallel with the Brownian motion was established [7]. From this stochastic approach, we can extract three stochastic parameters, using the Brownian motion equation to characterize the speckle pattern: Hurst coefficient, the size of the self-similar element, and the saturation of the variance. A study of the statistical properties of the speckle according to this approach was thus undertaken in order to discriminate speckle patterns for applications concerning dermatologic pathologies. We have there the first results obtained, on the psoriasis pathology and on irradiated pig skin. After having to evoke the material and the method used for theses applications in the second Section, we will show our first results in the third Section and we will discuss these results in Section four before concluding.

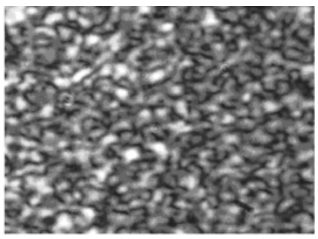

Figure 1: The speckle pattern of a scattering medium

Materials and methods

S.Guyot and al. showed the correlation between the statistics of the speckle and the statistic of Brownian motion [7]. Indeed, their first order statistics are of the same nature: Gaussian for the distribution in amplitude

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and in exponential decreasing for the distribution in intensity. Theirs statistics of second order have also the same characteristics: their power spectral density (PSD) present a decrease in $1/f^{\beta}$ (where f is a frequency and β a coefficient contained between 0 and 1) and their increment are Gaussians in the both case. Nevertheless, the PSD of the experimental figures decreases according to a power law only for high frequencies, which confirms self-similarity behaviour in this spectral field, contrary to the classic Brownian motion model which it, is self-similarity for all frequency domains. The optical properties of the medium, not taken into account in the statistic theory of the speckle, can be at the origin of this divergence. This is the reason why the generalization with the fractional Brownian motion was considered. Figure 2 shows typical power spectral densities of the speckle pattern (in log-log scales) where we can see the comportment in $1/f^{\beta}$ at high frequencies, characterizing a self-similar behaviour.

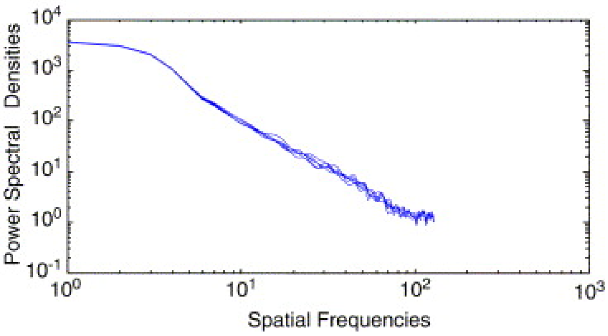

Figure 2: Power spectral density of speckle patterns (log scale)

Then, speckle phenomenon can be characterized by a fractional Brownian motion process which can be described by the function of diffusion:

$$\left\langle \left| X(t+\Delta t) - X(t) \right|^2 \right\rangle \propto \left| \Delta t \right|^{2H}$$

$$\log\left(\left\langle \left| X(t+\Delta t) - X(t) \right|^2 \right\rangle \right) \propto 2H \log(\left| \Delta t \right|) \qquad (1)$$

Where $\langle \ \rangle$ are the mean, $| \ |$, the norm and $\propto$ the proportional sign. For an image, time is replaced by space variables and X by the intensity. The function of diffusion (1) of a speckle pattern is represented on figure 3.

Two zones are distinguished: the linear part where the average variance seems to increase linearly in an interval of the neighbour enough narrow and a zone of "saturation" in which the average variance is nearly constant. The slope of the linear part corresponds to H, the Hurst coefficient. It is related to fractal dimension D_f of the image according to the expression $D_f = d + 1 - H$ where d is the geometric dimension. It characterizes the fractal dimension of the image, it is then a characteristic of the grains of speckle. It is also a parameter of local regularity. Note that this linear part indicates the self-similarity of the process. One can then extract three parameters from this function of diffusion: the Hurst coefficient H, the saturation of the variance Ga, and the characteristic size of the self-similar element R. This last parameter allows to evaluate dimension in the image, dimension which separates self-similar and classical behaviour. The saturation of the variance gives us the asymptotic direction at large neighbour in the image.

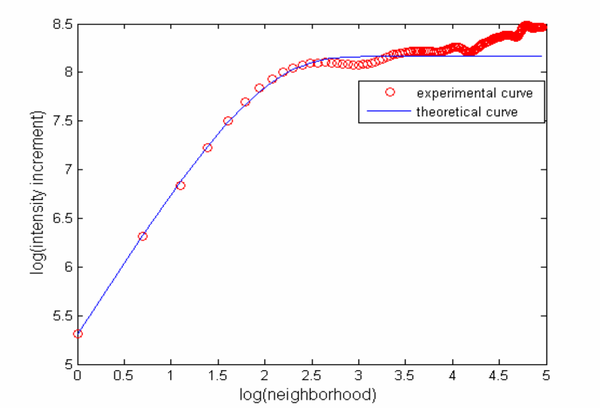

Figure 3: Log-log graphical representation of the speckle diffusion function of the speckle pattern shown in fig.1 (u.a.)

Figure 4 presents our experimental setup. It includes the following:

1. An unpolarized HE-NE laser (632.8nm) of about 5mW power.
2. A camera CCD Sony DXC-107 (without optical device), with 768*494 pixels. The camera has a sensitivity of 4.5 luxes and allows a time for capturing the speckle of 1/2000 S.
3. A scattering medium consisting of pig skin or human skin
4. Two linear polarizers at the input/output of the device (not used here).

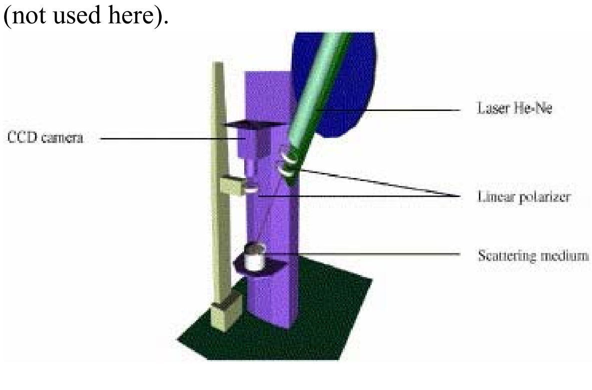

Figure 4: Experimental setup.

One of the cutaneous applications of this method was carried out: diagnostic of the psoriasis in an early stage. The light beam illuminates each zone, the healthy and pathological zone. For each zone, one series of 200 speckle patterns was carried out. For each speckle

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pattern, the three stochastic coefficients, H, R and Ga, were calculated according to the method described above. This provides the statistical characteristics of the speckle corresponding to this zone: from theses 200 images, one deduces an average value of each three stochastic parameters and the dispersion of these.

Another application was carried out, within the framework of a Project which began this year, with the collaboration of several laboratories concerning the study of the cutaneous radiological burn. Within the framework of this project, two pigs of type mini-pigs were irradiated by gamma radiation of ^{132}Cs, in CRSSA[1] (Grenoble, France):

- One mini-pig (pig A) was irradiated on two distinct areas, located on the right side, with 10 Gy and 15 Gy respectively.
- The other (pig B) was irradiated on a dorsal zone with 50 Gy.

Two series of measurements for each pig were realized: the first, 51 days after irradiation for the pig B and 150 days for pig A; the second, 79 days after irradiation for the pig B and 178 days for the pig A.
The results obtained for the two series of measurements correspond to an acquisition times to 1/2000 s. For each zone (pathologic and healthy zone), 3 points of measurements were carried out with 300 speckle patterns for each point.

Results

Let us consider the results for the psoriasis pathology.
The method proved to be sensitive: the exploitation of the speckle patterns allowed a discrimination of healthy and pathological skin. The results are presented in Table 1.

Table 1: Results for psoriasis

Zones	Hurst coefficient, H	Self-similarity, R	Saturation of the variance, Ga
Healthy	0.74±0.02	6.82±1.52	4.48±0.08
Pathological	0.49±0.01	17.28±4.25	3.43±0.14

Hurst coefficient and saturation of the variance are smaller for pathologic zone (of 33% for H and of 23% for Ga approximately) contrary to the size of the self-similar element (it is greater of 50% approximately).
We can note that dispersion to the measures is acceptable in spite of cutaneous dynamics related for to blood flow. We have a dispersion of 25% for R, 2% for H and 4% for Ga. R has a larger dispersion but it is very discriminating. The saturation of the variance, Ga is the criterion the least discriminating. The exploitation of the speckle pattern allows a discrimination of healthy and pathological tissues.

[1] Centre de Recherches du Service de Santé des Armés

Now, let us consider the results of the irradiated pig skin.
For each speckle pattern, the three stochastic coefficients H, R and Ga, were calculated. The average values of each 3 coefficients on the 300 speckle patterns to a point of measurement or on the whole of the speckle patterns of the 3 points of measurement, do not allow to discriminate the healthy of the irradiated zone (see figure 5). Then, the histograms of these three coefficients were realized. For the two pigs and for this two series of measurements, the distributions for the healthy and pathological zones were carried out for each stochastic parameter. In order to reduce the writing, here, we represent for each pig, the distribution of only one coefficient. For each distribution, we calculated the asymmetry coefficient except when two modes were observed. The whole results are represented in tables 2 and 3.
Let us consider the results obtained for pig A presented on the figure 5 and on table 2.
- Pig A: The results at J+150 and at J+178 cannot be compared because the three coefficients obtained for the healthy zone, corresponding to a reference zone, are very different from one series of measurement to another. We can see that for the self-similarity coefficient in figure 5. So, we cannot discuss a possible evolution in the time of these results. This shows that the method is sensitive, many parameters may influence the measurements.

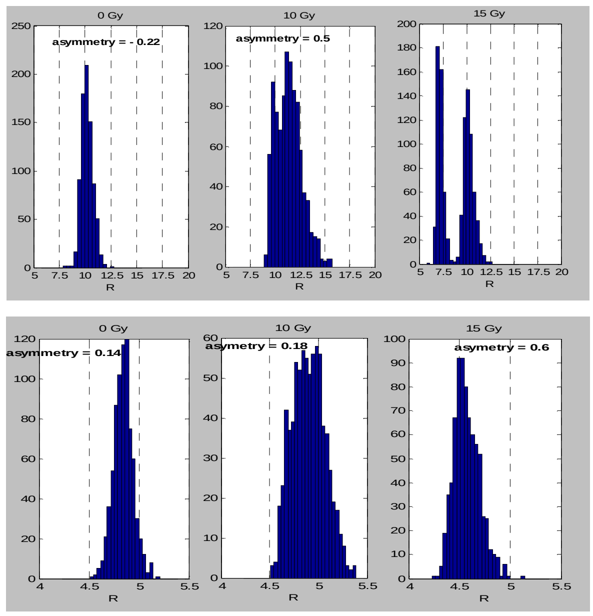


Figure 5: distribution for the pig A, for the self-similarity coefficient and for J+150 (graph of the top) and J+178 (graph of bottom).

We observe two modes only for 15 Gy at J+150. At this same date, the distributions of R and Ga for 10 Gy are more asymmetrical than those of 0 Gy (see table 2). At

J+178, the asymmetry is also greater for the distributions of the irradiated zones, and all the more that the irradiation dose is important. Moreover, the distributions for the irradiated zones and for this two series of measurement are wider than those of 0 Gy, as we can see it for the self-similarity coefficient in figure 5.

Table 2: Asymmetric coefficient for the distributions of the 3 parameters and for each zone, irradiated or non-irradiated, for the pig A at J+150 (of the top) and at J+178 (of bottom)

Pig A J+ 150	**0 Gray**	**10 Grays**	**15 Grays**
Hurst, H	Asymmetry = - 1.56 1 mode	Asymmetry = - 0.54 1 mode	Non exploited 2 modes
Self-similarity, R	Asymmetry = - 0.22 1 mode	Asymmetry = 0.50 1 mode	Non exploited 2 modes
Variance saturation, Ga	Asymmetry = - 0.16 1 mode	Asymmetry = 0.36 1 mode	Non exploited 2 modes

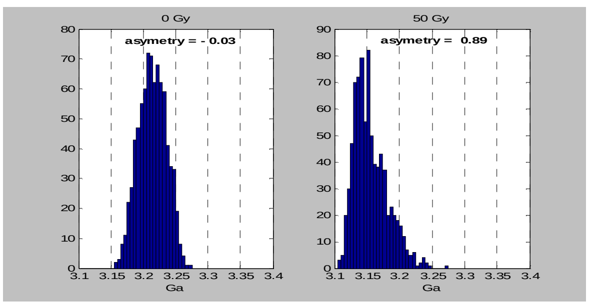
Pig A J+ 178	**0 Gray**	**10 Grays**	**15 Grays**
Hurst, H	Asymmetry = - 0.12 1 mode	Asymmetry = - 0.44 1 mode	Asymmetry = - 0.53 1 mode
Self-similarity, R	Asymmetry = 0.14 1 mode	Asymmetry = 0.18 1 mode	Asymmetry = 0.6 1 mode
Variance saturation, Ga	Asymmetry = - 0.03 1 mode	Asymmetry = 0.075 1 mode	Asymmetry = 0.6 1 mode

Now, let us consider the results obtained for the pig B represented on the figure 6 and table 3.

- Pig B: Once again, we cannot compare the results of the two series of measurements with J+51 and J+79, for the same reasons as previously.

At J+51 the distributions of R and Ga are symmetrical for the non-irradiated zone. For 50 Gy, a strong asymmetry is noted, for the same coefficients (0,96 for R et 0,89 for Ga).

Moreover, we note two modes for 50 Gy with H at J+51, and for R and Ga at J+79 (see figure 6 for the example of Ga).



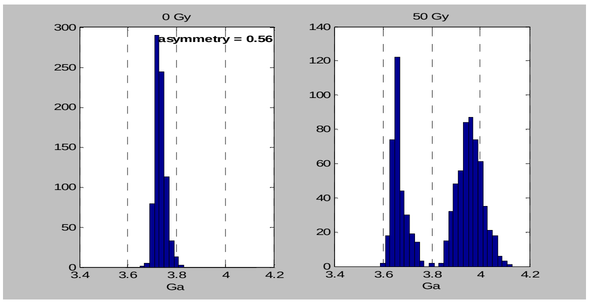


Figure 6: distribution for the pig B, for the saturation of the variance coefficient, Ga and for J+51 (graph of the top) and J+79 (graph of bottom).

Table 3: Results for the distributions of the 3 parameters and for each zone, irradiated or non-irradiated, for the pig B at J+51 (of the top) and at J+79 (of bottom)

Pig B J + 51	**0 Gray**	**50 Grays**
Hurst, H	Asymmetry = 0.23 1 mode	Non exploited 2 modes
Self-similarity, R	Asymmetry = 0.076 1 mode	Asymmetry = 0.96 1 mode
Variance saturation, Ga	Asymmetry =- 0.03 1 mode	Asymmetry = 0.89 1 mode

Pig B J + 79	**0 Grays**	**50 Grays**
Hurst, H	Asymmetry = - 0.3 1 mode	Asymmetry = - 0.18 1 mode
Self-similarity, R	Asymmetry = 0.67 1 mode	Non exploited 2 modes
Variance saturation, Ga	Asymmetry = 0.56 1 mode	Non exploited 2 modes

To test the response of a pig according to the irradiation dose, we calculated the differences of the asymmetry coefficient of the distributions, between each irradiated zone (10, 15 and 50 Gy) and the healthy zone. These differences were calculated for the same animal and from images captured during the same experiment. Without making distinction neither between the pigs nor between the two series of experiments, the average of these variations was calculated for a given dose. Figure 7 shows the results of this treatment.

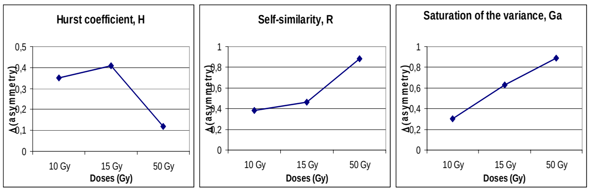


Figure 7: Evolution of asymmetry of the distributions of the irradiated zones in function of the irradiation doses; for the distributions of H, R and Ga.

We note, according to this figure, a strong growth of the asymmetry coefficient according to the dose, for R and Ga.

Discussion

In a first time, note that the mediocre sensitivity of the CCD camera impose a relatively long acquisition time. So, on the one hand, the least luminous grains of specke are not captured, and on the other hand, the speckle pattern can contain many grains superposed. Consequently, the estimation of the three coefficients gives not perhaps a description of the real speckle.

This causes a loss of information and thus prevents from having results finer. So, the discrimination is thus more difficult. Also, it is difficult to discuss the validity of the results owing to the fact that this approach of speckle phenomenon was recently introduced into the literature.

Concerning the results of the psoriasis, two of the three stochastic parameters, allow a good discrimination of the pathological zone: the Hurst coefficient, H and the size of the self-similar element, R.

The values of these three parameters are established starting from successive measurements (25 images/s) and H and Ga seems not to be very sensitive to the temporal variations from one measurement to another. On the contrary, the fluctuations of R are more important. Two explanations are possible:

- Mathematical reason: From the diffusion curve, log(R) is calculated and R is deduced, consequently, by an exponential, what amplifies its variations.
- Physical reason: H, R and Ga are averages values on 200 successive acquisitions of images. In the image, H is a local measurement, it is related to the grain of speckle, and Ga is a global characteristic. They do not have reason to vary strongly from one measurement to another. R characterizes the separation of self-similarity behaviour and classic behaviour. Thus, if we suppose that R corresponds to a measurement related to the distance inter-grain in the image, the temporal fluctuations from one image to another, due to the dynamics of the medium, will have more effects on the result of R values. This would allow to understand the strong fluctuations of R.

Too many physiological factors interfere to establish now a link between these coefficients and the optical or biological properties of the medium. This method allows before all a discrimination of tissues and thus makes it possible the medical follow-ups, if a sample of sufficient size confirms it.

These three parameters allowed discriminate various speckle patterns coming from skin reached of psoriasis. However, contrary to the case of the psoriasis, the healthy zones and irradiated zones are identical with the naked eye. It is perhaps the reason why, discrimination by the three coefficients values cannot be currently established. An experimental setup more sensitive could correct this problem.

However, this treatment shows us several things about the pig skin irradiated:

- We cannot compare for the same pig the results of two different series of measurements; other biological or experimental parameters must influence these results.
- We always observe, either, a stronger asymmetry of the distribution of the zone irradiated compared to the healthy zone, and this is all the more marked that the dose is important; or an unfolding of the distribution (presence of two modes) for the zone irradiated.

We can make an assumption on the presence of these two modes: it can correspond to different acquisition points. According to this assumption, one point of the same zone would have statistical properties and thus optical properties very different than a nearby point. Moreover, these two modes are observed only for irradiated zones. This is perhaps the mark of a greater heterogeneity of the irradiated skin, whose points could have optical properties very different than a nearby point due to the irradiation. It is true that, from a biological point of view, the response of the tissue to the irradiation is very heterogeneous. It would be necessary, to check it, make acquisitions on a greater number of points of measurements and separate them in the data treatments.

From these results, we cannot conclude on the significance of the strongest asymmetries observed on the distributions of the zones irradiated compared to those observed on the healthy zones, nor why this greater asymmetry is not always present for Hurst coefficient.

Although these observations correspond only to preliminary experiments, they seem to indicate that asymmetry would be a possible criterion of discrimination and can be a criterion of quantification of the dose.

It is envisaged, in order to limit the loss of information caused by the movement of the animal because of its breathing, to make a selection of the most stable images i.e. those corresponding to the immobility of the animal.

Conclusions

We presented here the first applications of the innovating approach for the statistic study of the phenomenon speckle, established by S.Guyot [7]. This approach, based on the fractal theory is powerful in front of the traditional method since it integrates the multi-scale aspect of the speckle. By modelling the

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speckle with the fractional Brownian motion, three statistical parameters are deduced from the curve of diffusion in intensity: the Hurst coefficient, the characteristic size of the self-similar element and the saturation of the variance.

These parameters allowed discriminate the healthy zone of the pathological zone in case of the psoriasis.

Contrary to the psoriasis, the irradiated skin, invisible with the naked eye, could not be discriminated rigorously from the healthy skin with the current experimental setup. However, the current results show that the healthy skin differs from the irradiated skin, via asymmetry coefficient or presence or not of the 2 modes. Perhaps, an experimental setup with a more sensitive camera would allow discrimination by these stochastic coefficients as in the case of the psoriasis.

We can extend the fractal analysis of the speckle by a structural approach, which consists to describe the speckle pattern by the fractal geometry. This structural approach, well known by the so called “box-counting method and Lacunarity evaluation”, completes the fractal statistics approach. The “box-counting method” makes it possible to calculate the fractal dimension. The lacunarity completes the fractal dimension and allows to measure the structural variations in the textures and inform us of their heterogeneities. We give a few references of these two approaches that we apply to our speckle pattern [8, 9, 10]. Currently, an experimental setup with a camera much more sensitive is used for discrimination, by the fractal structural approach, of object of different roughness. Soon, tests in vivo, with this same camera, will be carried out regularly on the irradiated pig skin with various doses.

In the next years, the objective will be, not only to discriminate various mediums, but also to go up with the modifications of the optical properties generated by the irradiation and to link it, by a cytogenesis and histological study on the biopsies, with the corresponding biological modifications.

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