Temperature regulation of microvascular flow: a multi-dimensional improved EMD-based study of laser speckle contrast images

Anne Humeau-Heurtier, Guillaume Mahé, Pierre Abraham

University of Angers, France

Hospital of Angers, France

e-mail: anne.humeau@univ-angers.fr

Outline

- Laser speckle contrast imaging
- Goal of the work
- Measurement procedure
- Image processing framework
- Results and Discussion

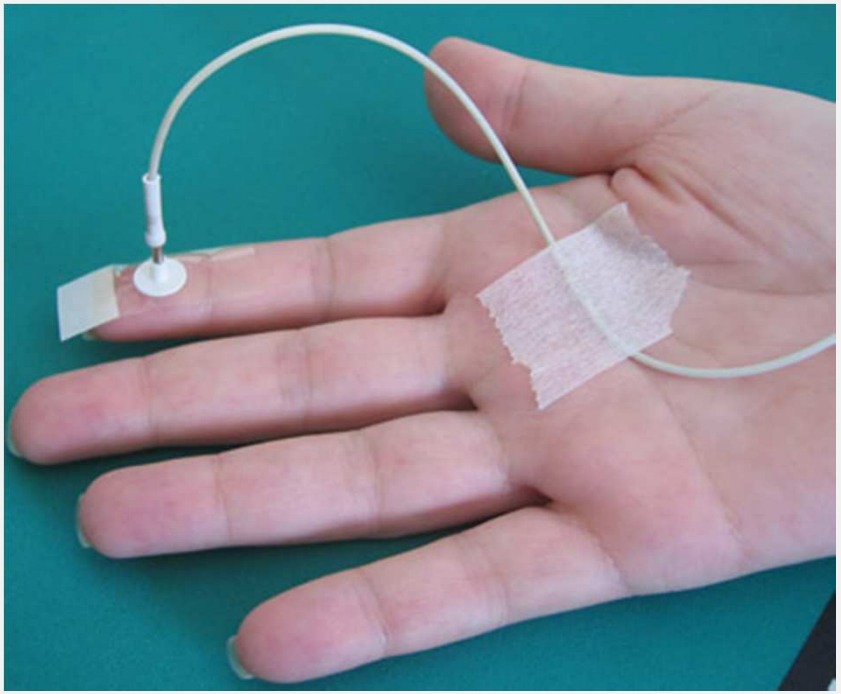
Laser Doppler flowmetry (LDF)

Laser Doppler flowmetry (LDF) has the following advantages

- ✓ Non invasive
- ✓ Real time

but it has the following drawbacks

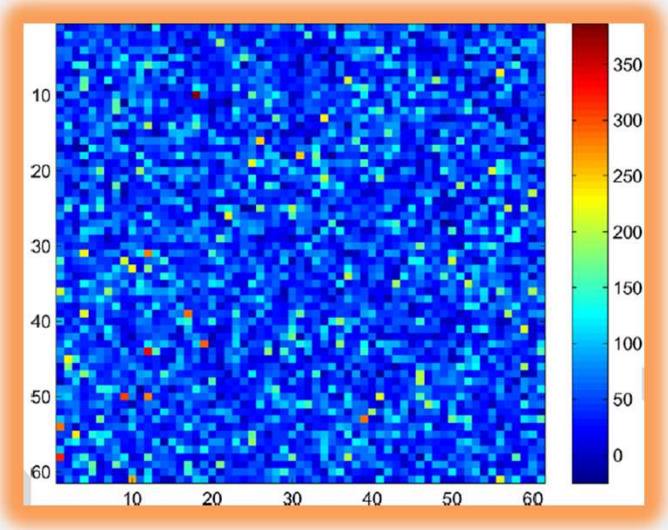
- ✓ With contact
- ✓ Low reproducibility



Laser speckle contrast imaging (LSCI)

Laser speckle contrast imaging (LSCI) has the following advantages

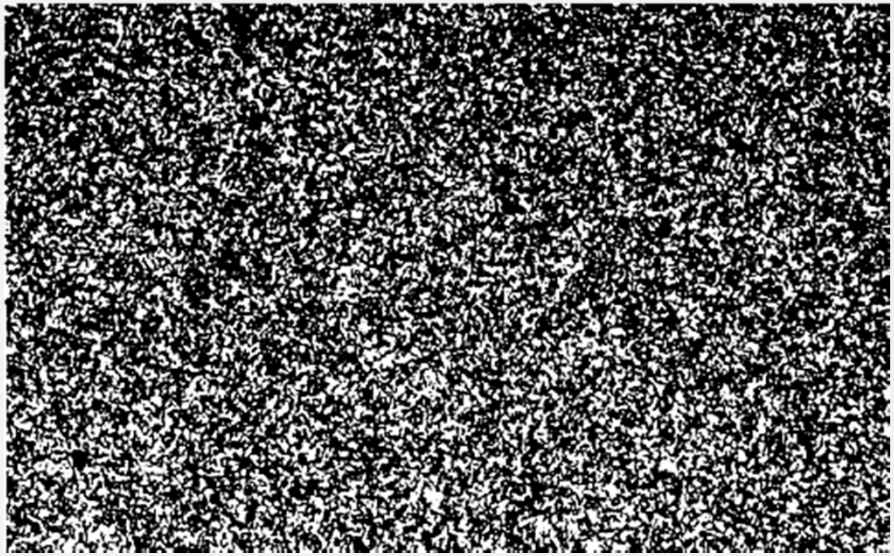
- ✓ Non invasive
- ✓ Without contact
- ✓ Reproducible



Laser speckle contrast image (61 rows and 61 columns) recorded at rest on the forearm of a healthy subject. The colorbar corresponds to perfusion values (APU_{LSCI})

Laser speckle contrast imaging (LSCI)

- The tissue under study is illuminated by a laser with an expanded beam
- The backscattered light forms an interference pattern (a speckle pattern) on the detector (video camera)



A typical speckle pattern

Laser speckle contrast imaging (LSCI)

- Motions of the particles in the illuminated tissue => dynamic speckled image on the camera

- Due to the exposure time of the camera, there is a blurring of the speckle pattern

Laser speckle contrast imaging (LSCI)

The **degree of blurring** is quantified as the local speckle contrast K value, as

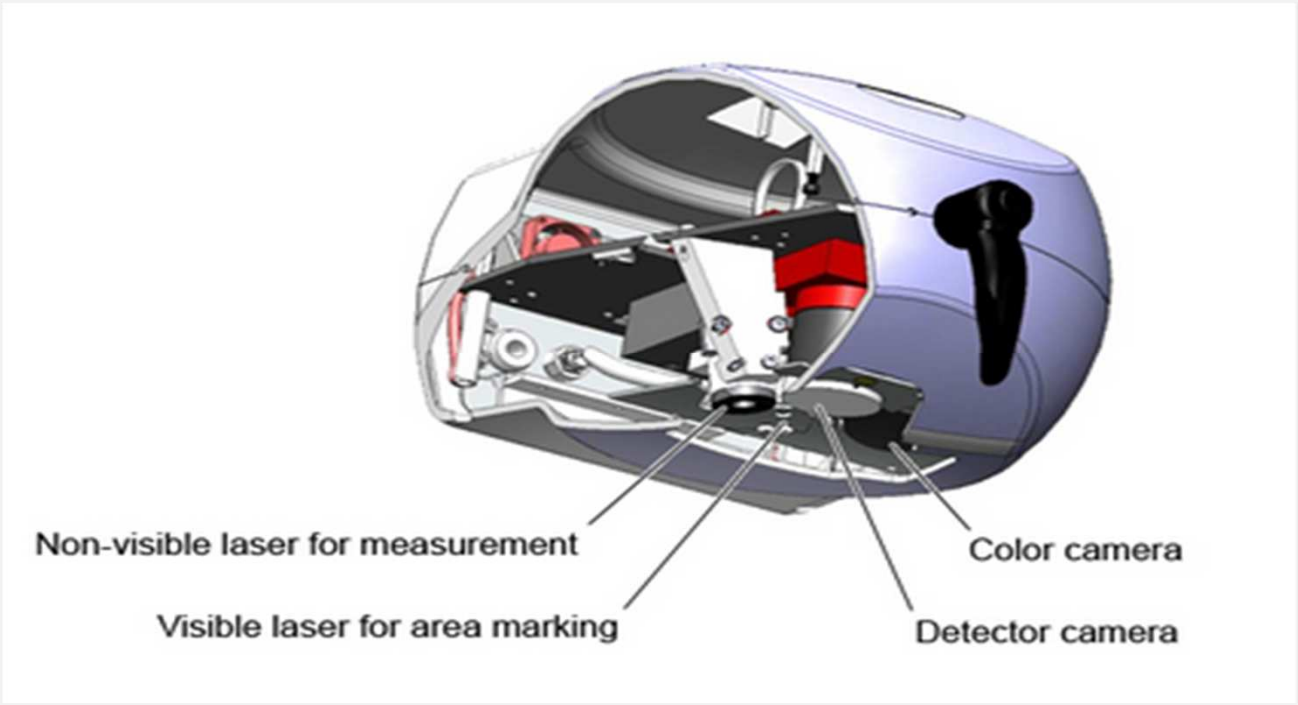
$$K = \frac{\sigma}{\langle I \rangle}$$

where σ refers to the spatial standard deviation of the speckle intensity and $\langle I \rangle$ is the mean intensity

Laser speckle contrast imaging (LSCI)

70 mW laser diode
Laser wavelength: 785 nm

Camera: exposure time of 6 ms



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Goal of the work

- Skin plays an important role in the body thermoregulation ↝ vasodilation and vasoconstriction
- Skin temperature varies with fever, exercise, environmental temperature variations…
- Our goal: to study locally **the variations of microvascular perfusion induced by variations of room temperatures**

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Measurement procedure

- 15 healthy subjects

- Microvascular perfusion was monitored on the right forearm with a laser speckle contrast imager (PeriCam PSI System, Perimed), **in two different room temperatures**: 17.2 ± 1.5°C and 31.4 ± 0.7°C

- The distance between the laser head to skin was set at 15 cm which gave images with a resolution around 0.4 mm

- At **rest**, during a 3-minute period of occlusion (**biological zero**, BZ), and during post-occlusive reactive hyperaemia (**PORH**)

Measurement procedure

- **Local cutaneous temperature was also measured** on the right forearm using a surface thermocouple probe connected to an electronic thermometer (BAT-12, Physitemp Instruments Inc.)
- A minimal interval of **one day separated each experiment**
- The **order** of studied temperatures was randomized
- **For each subject** and for each room temperature, **three images have been processed: rest, BZ, PORH**

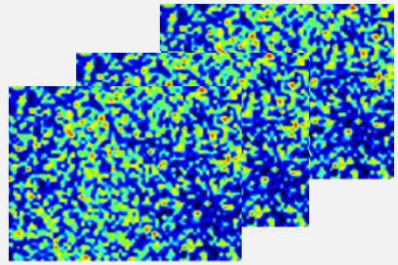

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Image processing framework

- We used the very recent multi-dimensional complete ensemble empirical mode decomposition with adaptive noise (**MCEEMDAN**) algorithm (Humeau-Heurtier *et al.*, IEEE Trans. Med. Imaging, 2015)

- CEEMDAN is a powerful tool for adaptive multi-scale analyses of non stationary and nonlinear signals (Colominas *et al.*, Biomed. Signal Process. Control, 2014)

- It is **fully data-driven** and leads to intrinsic mode functions (IMFs)

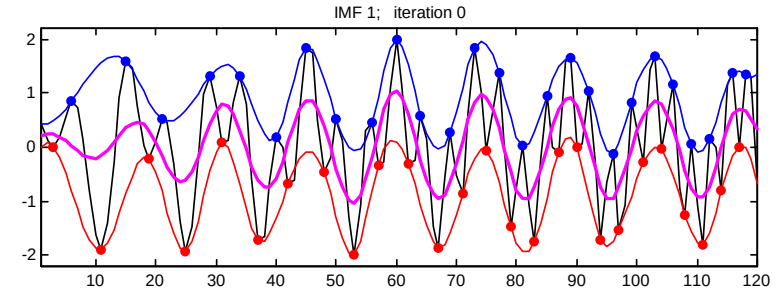
Image processing framework

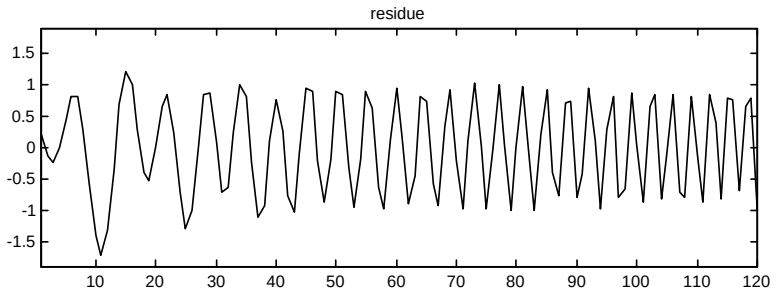
- Principles of EMD
  - each IMF represents a narrow band frequency-amplitude modulation that often corresponds to a specific physical phenomenon
  - for a discrete signal $x[n]$ EMD decomposes x in IMFs IMF_k and a residual component R as

$$x[n] = \sum_{k=1}^{K} IMF_k[n] + R[n],$$

Image processing framework

- Principles of EMD





For a discrete signal $x[n]$ the EMD algorithm is the following [24]

1) identify all extrema of the signal $x[n]$
2) interpolate between minima (respectively maxima), ending up with some "envelope" $e_{min}[n]$ (respectively $e_{max}[n]$)
3) compute the average $m[n] = (e_{min}[n] + e_{max}[n])/2$
4) extract the detail $d[n] = x[n] - m[n]$
5) iterate on the residual $m[n]$

Use of a sifting process (an inner loop that iterates steps (1) to (4) upon the detail signal $d[n]$) until the detail signal $d[n]$ can be considered as zero mean from the stopping criterion

This leads to a detail considered as the effective IMF

Afterwards the corresponding residual $m[n]$ is computed and then step (5) applies

Image processing framework

- **The CEEMDAN algorithm relies on the following steps** (Colominas *et al.*, Biomed. Signal Process. Control, 2014)

1) use EMD to obtain the local means of I realizations $x^{(i)} = x + \beta_0 E_1(w^{(i)})$. This leads to the first residue: $r_1 = \langle M(x^{(i)}) \rangle$
2) at the first stage ($k = 1$) calculate the first mode $\tilde{d}_1 = x - r_1$
3) compute the second residue as the average of local means of the realizations $r_1 + \beta_1 E_2(w^{(i)})$. Define the second mode as $\tilde{d}_2 = r_1 - r_2 = r_1 - \langle M(r_1 + \beta_1 E_2(w^{(i)})) \rangle$
4) for $k = 3, \ldots, K$, compute the kth residue as $r_k = \langle M(r_{k-1} + \beta_{k-1} E_k(w^{(i)})) \rangle$
5) compute the kth mode as $\tilde{d}_k = r_{k-1} - r_k$
6) go to step 4 for next k

$w(i)$ is a realization of white Gaussian noise with zero mean and unit variance, $M()$ is the operator which produces the local mean of the signal that is applied to, $E_k()$ is the operator that produces the kth mode with EMD and β_k allows the selection of the SNR at each stage

- **Compared to EEMD, CEEMDAN provides a better spectral separation of the modes and requires lesser number of sifting iterations to obtain the IMFs (Torres *et al.*, ICASSP, 2011)**

Image processing framework

- **MCEEMDAN**
  - separation of the original data into one-dimensional slices
  - application of the CEEMDAN algorithm to each one-dimensional slice
  - the reconstruction of IMF is based on a comparable minimal scale combination principle (Humeau-Heurtier *et al.*, IEEE Trans. Med. Imaging, 2015)
  - the first IMF represents the smallest scale or the finest textural, while the last one gives only the largest scale of the overall mean trend in intensity of the image

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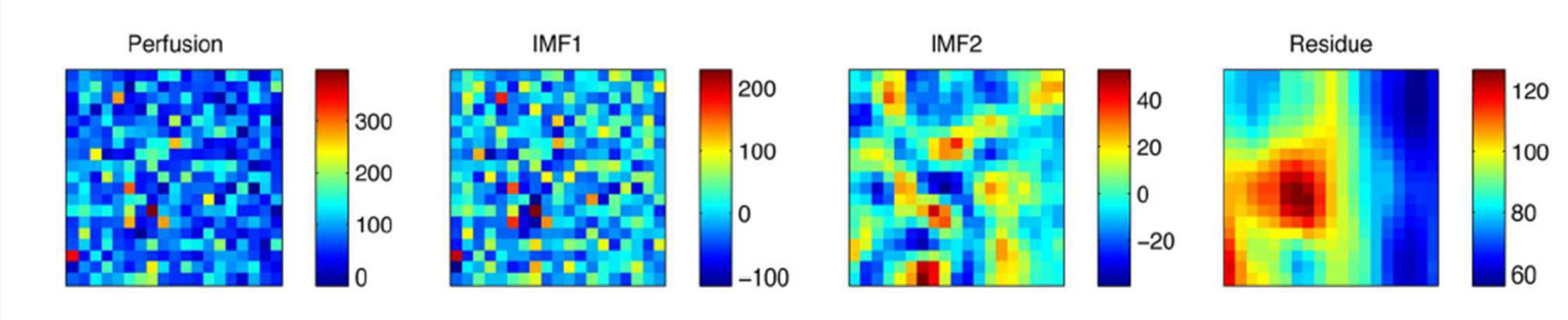
Results and Discussion

- The **local cutaneous temperatures** obtained by the low and high room temperatures were **28.0 ± 2.0°C and 34.1 ± 1.3°C**, respectively
- We herein propose to extract 2 IMFs + a residue, for each image processed
- IMFs and residue of LSCI data present local patterns

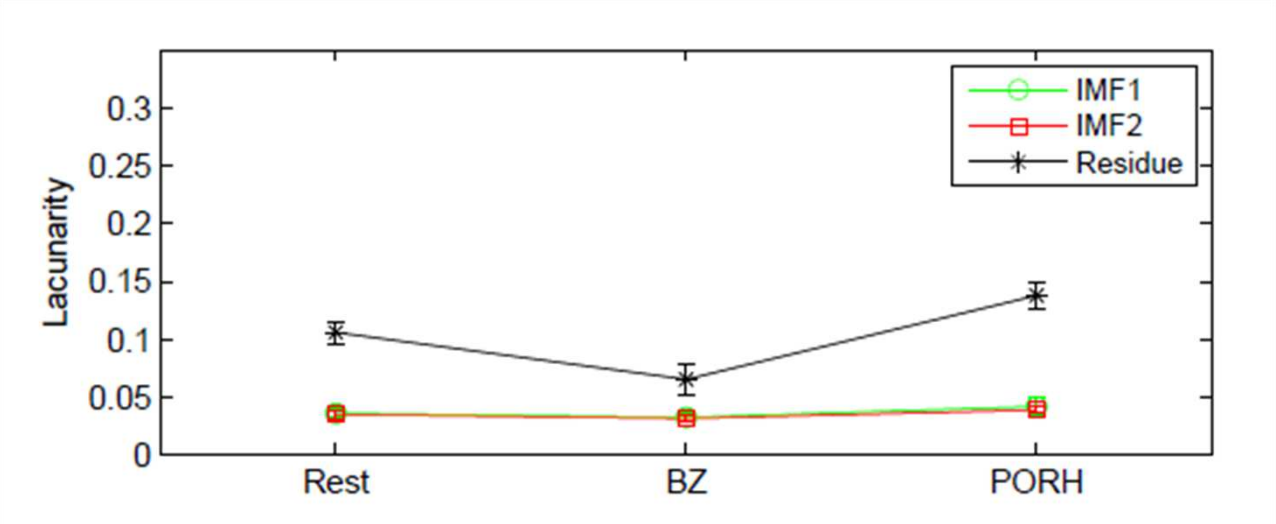


MCEEMDAN results at rest for the high room temperature

Results and Discussion

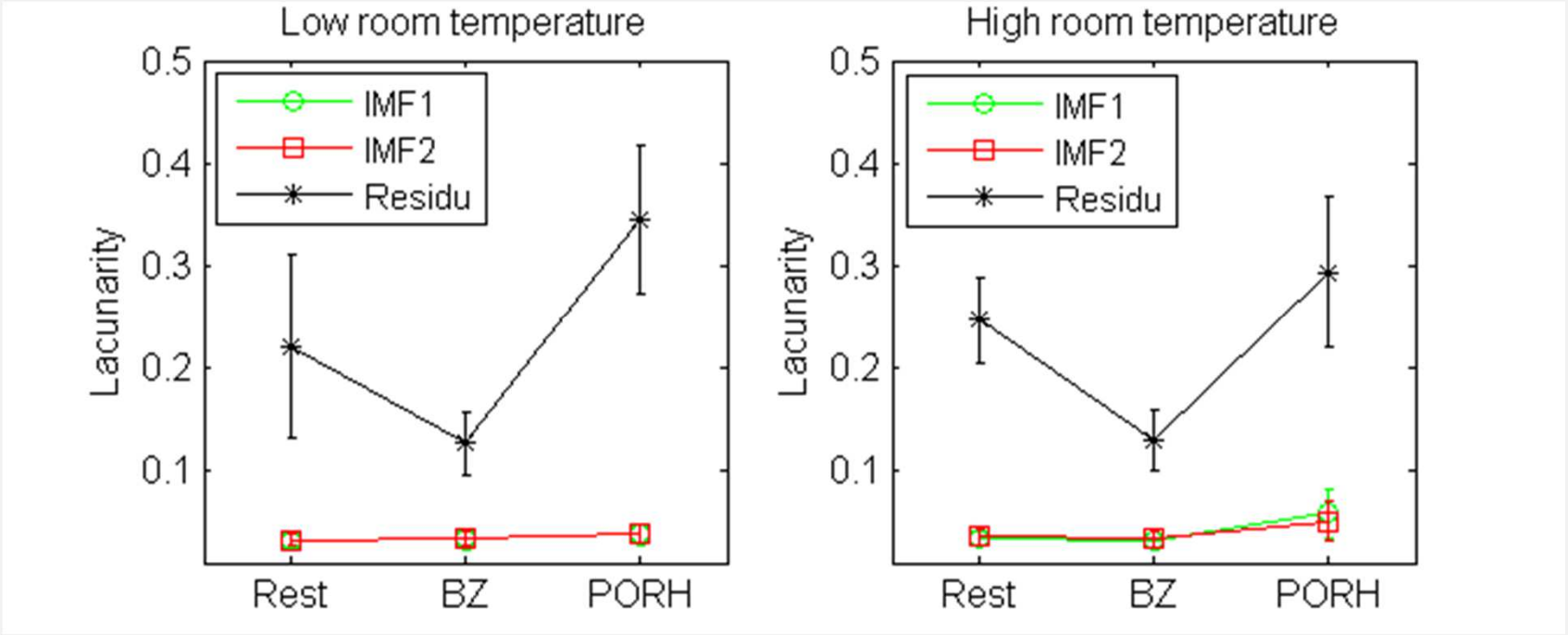
- Similar patterns have already been shown in ambient temperature
- They have been quantified with **lacunarity** of the fractal dimension image for each IMF and residue
- Lacunarity enables to differentiate patterns of spatial dispersion. The higher the lacunarity, the more inhomogeneous the examined fractal area and *vice versa*

Results and Discussion



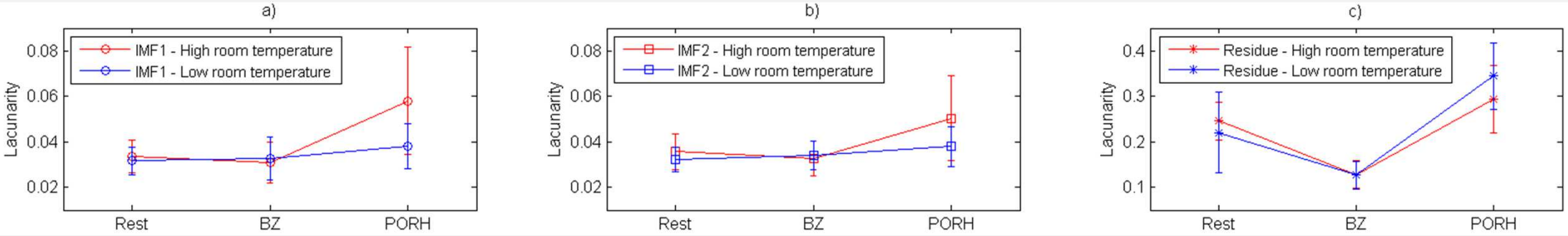
Lacunarity values of fractal dimension image for IMFs and residue obtained when choosing MCEEMDAN decomposition with 2 IMFs and residue. The results have been computed from LSCI data recorded in 10 healthy subjects at ambient temperature (Humeau-Heurtier *et al.*, IEEE Trans. Med. Imgaging, 2015)

Results and Discussion



Lacunarity values of fractal dimension image for IMFs and residue obtained when choosing MCEEMDAN decomposition with 2 IMFs and residue

Results and Discussion



Lacunarity (average and standard deviations computed from 15 subjects)
of fractal dimension images for a) IMF1; b) IMF2; c) residue, given byMCEEMDAN

- We observe that, for the finest textural (IMF1 and IMF2), low skin temperature reduces the lacunarity value at rest and at PORH, compared to the high skin temperature.
- By opposition, for the largest spatial scales (residue), the lacunarity value is the highest for the lowest skin temperature, at PORH

Results and Discussion

- This has to be studied more deeply to understand the physiological phenomena coming into consideration, and to know why different results are observed at different spatial scales

- In the future, it could be interesting to compare these results with those obtained in patients with microvascular dysfunctions

- MCEEMDAN could become an easy way to extract hidden patterns from laser speckle contrast images and – from them – to differentiate different physiological states