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Fourier-Transform Infrared Microspectroscopy (FT-IR) Study on *Caput* and *Cauda* Mouse Spermatozoa †

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† Presented at the 6th International Electronic Conference on Sensors and Applications, 15–30 November 2019; Available online: https://ecsa-6.sciforum.net/.

Published: 22 January 2020

Abstract: Fourier-Transform Infrared micro-spectroscopy (μFT-IR) was used for an in vitro investigation on spermatozoa (SPZ) samples separately collected from *caput* and *cauda* of mouse epididymis. SPZ are characterized by deep biochemical changes during the transit along the epididymis and they can constitute ideal candidates for a μFT-IR investigation, thanks to the ability of this technique in analyzing cells at a molecular level. Appreciable differences were reported in the infrared spectra from *caput* and *cauda* SPZ, and biochemical changes in protein, nucleic acid, lipid, and carbohydrate content of cells were evidenced. The present investigation indicates that μFT-IR can constitute a valuable tool for monitoring, in an easy and fast way, the changes suffered by SPZ during the transit along the epididymis.

Keywords: *caput* and *cauda* spermatozoa; μFT-IR microspectroscopy; protein; nucleic acid; lipid and carbohydrate components

1. Introduction

Fourier-Transform IR (FT-IR) spectroscopic technique is nowadays a very valuable tool for the nondestructive analysis of biological specimens. FT-IR results are also particularly useful in cytological and histological diagnosis by using imaging procedures [1]. FT-IR is able to reveal bonds presenting a change of dipole moment during vibrational motion. These vibrational modes can be quantitatively characterized by IR spectroscopy, providing a very sensitive, label-free tool for studying molecular composition and dynamics without perturbing the sample. When FT-IR spectroscopy is performed on biological materials, the most important spectral regions are the fingerprint region (600–1450 cm^{-1}) and the amide I and amide II (amide I/II) region (1500–1700 cm^{-1}). The higher-wavenumber region (2800–3500 cm^{-1}) is due to stretching vibrations such as S-H, C-H, N-H and O-H, whereas the lower-wavenumber regions typically correspond to bending and carbon skeleton fingerprint vibrations. These regions are able to give a complete biochemical fingerprint of the structure and function of investigated samples and have been adopted in a very large number of different samples of biological interest.

Recently, FT-IR spectroscopy has been adopted for investigating spermatozoa (SPZ) samples in order to principally take advantage of its non-invasivity. In particular, cyanide toxicity effects on rat sperm have been investigated at a molecular level by using FT-IR technique. Cyanide compounds are largely used in industries and are considered to be a ubiquitous pollutant in the environment.

The use of FT-IR spectroscopy has also allowed an investigation on the secondary structure of protein components. It is worth noting that a complementary vibrational technique, the Raman technique, has been used for investigating oxidative DNA damage in human sperm [2].

In the present paper, FT-IR microspectroscopy (μFT-IR) has been adopted for characterizing SPZ separately collected from *caput* and *cauda* of the epididymis. Interestingly, SPZ are transcriptionally and translationally silent cells. During the epididymal transit, from *caput*-to-*cauda*, these cells undergo maturation via massive biochemical changes [3,4] that include: (i) decreases of cholesterol; (ii) qualitative composition of cytoplasmic proteins and RNA; (iii) protein degradation and phosphorylation; (iv) acquisition of GPI-anchored membrane proteins; (v) proteolytic remodelling of membrane proteins; (vi) fatty acid composition from saturated to polyunsaturated forms; (vii) DNA methylation; and (viii) inter/intra protamine disulfide-bound formation. Due to their remarkable biochemical differences, *caput* and *cauda* SPZ can be considered ideal candidates for an FT-IR spectroscopy investigation.

In this report, we summarize the preliminary results of an investigation on mouse sperm samples from *caput* and *cauda* epididymis. To our knowledge, this is the first time that vibrational spectroscopies are adopted for investigating the changes occurring in SPZ during the epididymal transit.

2. Materials and Methods

2.1. Collection of Sperm Samples from Caput and Cauda Epididymis

Adult male mice (CD1 background, from Charles River Laboratories, Lecco, Italy) were euthanized by asphyxia with CO_2 and epididymis were dissected for sperm collection. Briefly, caput and cauda epididymis were separately immersed in PBS (pH 7.6) and slightly cut to endorse sperm extrusion from the epididymal duct, as previously reported [5]. Spermatozoa samples, separately collected from *caput* and *cauda* epididymis, were filtered throughout cheesecloth, washed by centrifugation (200× *g* for 5 min), in 0.9% NaCl solution, and pellets were processed for FT-IR analysis.

All animal studies were carried out in accordance with the principles and procedures outlined in the National Institute of Health Guide for Care and Use of Laboratory Animals and approved by the Italian Ministry of Research and the Italian Ministry of Health.

2.2. FT-IR Spectral Analysis

For FT-IR spectral analysis, SPZ pellets were resuspended in 0.9% NaCl solution and drops of a few microliters were used for spectra acquisition. For this purpose, a Perkin Elmer Spectrum One FT-IR spectrometer equipped with a Perkin Elmer Multiscope system infrared microscope (Mercury Cadmium Telluride detector, Perkin Elmer Inc., Hopkinton, MA, USA) was used. Spectral acquisitions were performed in specular-reflection mode with thin layers of samples (2 L) put on metallic IR-reflective surface. The background spectrum was collected from the metallic IR-reflective surface without sample. A sampling spot on the surface was selected through an objective (l0× optical or 15× infrared). All spectra were collected using 64 scans in the range from 4000 to 600 cm^{-1} with a 4 cm^{-1} spectral resolution.

The spectra were preliminarily analyzed using the application routines provided by the software package ("Spectrum" User Guide, Perkin Elmer Inc., Hopkinton, MA, USA) controlling the whole data acquisition system. "Spectrum" (release 5.0.2, 2004) is the main Perkin Elmer software package for collecting, viewing and processing IR spectra [6].

3. Results and Discussion

The μFT-IR average spectra of mouse SPZ samples from *caput* and *cauda* epididymis (*caput* and *cauda* SPZ) were obtained in the 4000–600 cm^{-1} range. The peak position and band assignments were done in agreement with [6]. In order to evidence the differences occurring between the two spectra, they were divided into four wavenumber ranges: 3600–3000 cm^{-1} (Figure 1), 3050–2800 cm^{-1} (Figure 2), 1800–1200 cm^{-1} (Figure 3) and 1200–600 cm^{-1} (Figure 4).

Figure 1 shows the average μFT-IR spectra of *caput* and *cauda* SPZ in the range of 3600–3000 cm^{-1}. In this range, there is the large contribution of amide A band (located at 3309 and 3290 for *caput* and *cauda* SPZ, respectively) due to N-H and O-H stretching modes of proteins and intermolecular H bonding. It is worth noting that the shape of this band changes between *caput* and *cauda* samples. In particular, for *caput* SPZ, the maximum is located at ~3400 cm^{-1}; conversely, for *cauda* SPZ, the maximum is located at 3290 cm^{-1}. A very weak contribution ~3070 cm^{-1} can be noticed only in the case of *cauda* samples and can be attributed to the N-H stretching of amide B. In order to analyze the changes in the lipid content of *caput* and *cauda* SPZ, the spectral region from 3050 to 2800 cm^{-1} was considered (Figure 2). In this region, it is possible to evidence the contributions of CH_3 asymmetric stretching (located at 2957 and 2959 cm^{-1} for *caput* and *cauda* samples, respectively), CH_2 asymmetric stretching (located at 2922 and 2924 cm^{-1} for *caput* and *cauda* samples, respectively), CH_3 symmetric stretching (located at 2875 cm^{-1} for both *caput* and *cauda* samples) and CH_2 symmetric stretching (located at 2851 and 2853 cm^{-1} for *caput* and *cauda* samples, respectively). It is important to note that the two spectra are largely different in shape and relative intensity of the main peaks, even though the position of the different CH_2 and CH_3 contribution does not change in a crucial way. In particular, the position of CH_2 symmetric stretching does not show significant changes, taking into account the spectral resolution of our equipment (4 cm^{-1}). This can indicate that no important changes in membrane fluidity occur [7]. In this region of the spectra, a contribution at 3013 cm^{-1} is also present which is more evident for *caput* SPZ samples. This band is usually assigned to an olefinic functional group in unsaturated lipids, mainly due to C-H stretching mode. This band can be used for further investigating lipid peroxidation in tissue [8].

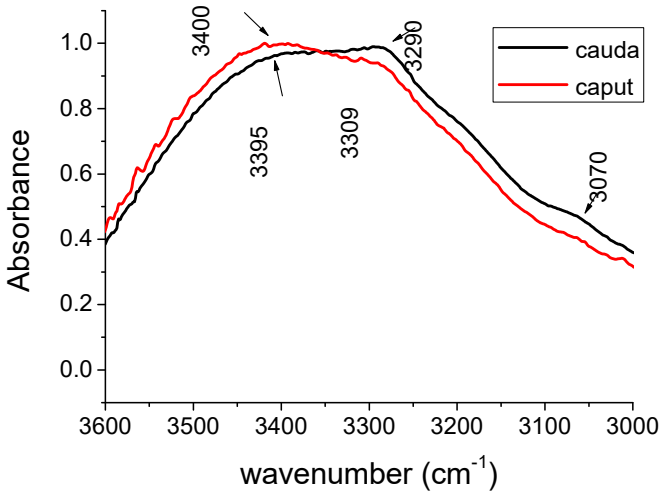

Figure 1. FT-IR spectra of caput and cauda sperm of WT mouse in 3600–3000 cm^{-1} region.

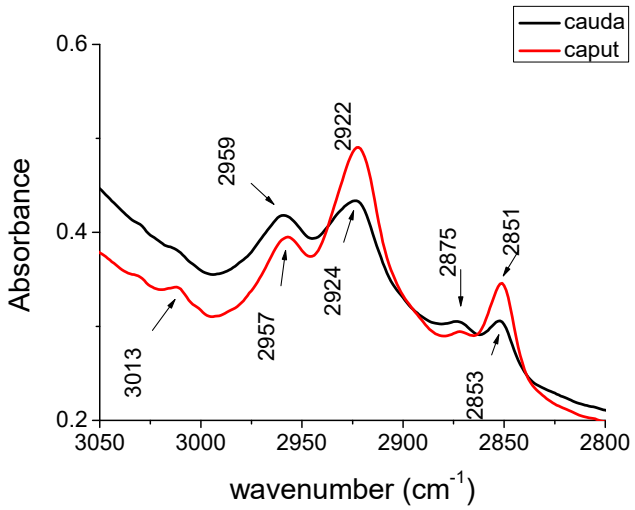

Figure 2. FT-IR spectra of caput and cauda sperm of WT mouse in 3050–2800 cm^{-1} region.

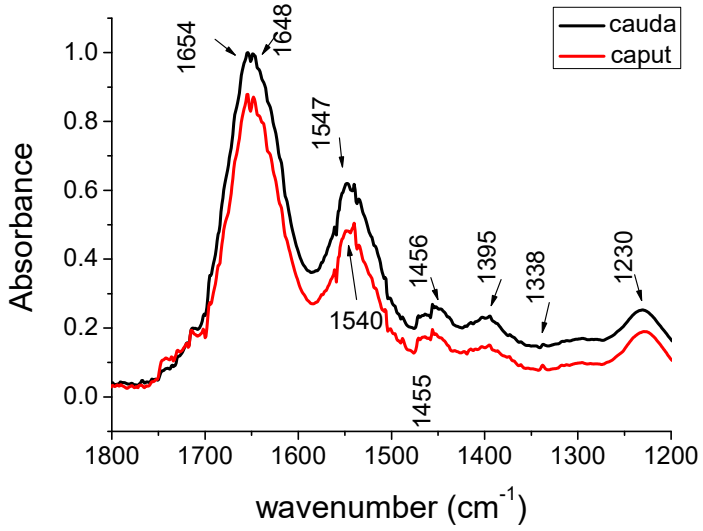

Figure 3. FT-IR spectra of caput and cauda sperm of WT mouse in 1800–1200 cm^{-1} region.

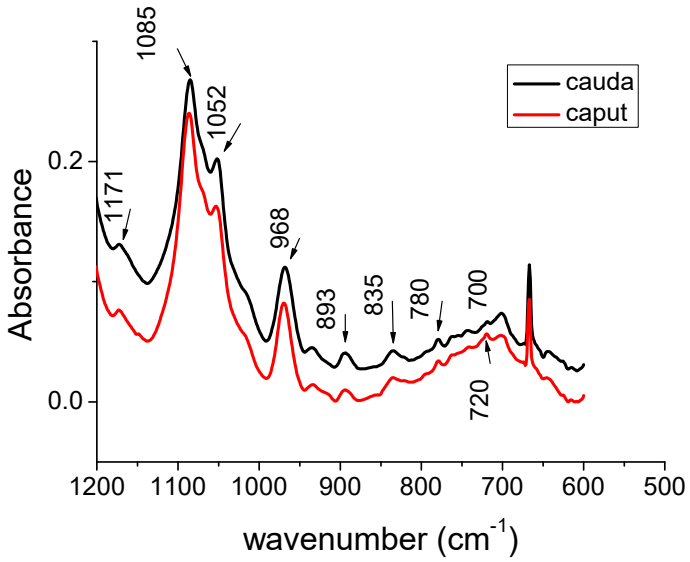

Figure 4. FT-IR spectra of caput and cauda sperm of WT mouse in 1200–600 cm^{-1} region.

In Figure 3, the 1800–1200 cm^{-1} region of μFT-IR spectra of *caput* and *cauda* SPZ is reported. In this region, the main contributions are due to protein content. In particular, the band due to the Amide I C=O stretching is positioned ~1650 cm^{-1} for the two different samples; however, differences can be noted in the band's shape. In Figure 3, the contributions of Amide II (at 1540 and 1547 cm^{-1} for *caput* and *cauda* samples, respectively) and Amide III (at 1300 cm^{-1} for both *caput* and *cauda* samples) are present. The small band positioned at 1455 and 1456 cm^{-1} for *caput* and *cauda* samples, respectively, can be due to CH_3 asymmetric bending and CH_2 scissoring mode that can be associated with lipid and protein contents. At 1395 cm^{-1}, a small feature can be noticed and it can be attributed to COO- symmetric stretching vibration mode related to fatty acids. The band located at 1230 cm^{-1} is due to PO_2^- asymmetric stretching mode related to nucleic acids and phospholipids contributions.

In Figure 4, the region of short wavenumber (1200–600 cm^{-1}) of μFT-IR spectra of *caput* and *cauda* SPZ is shown. This region is mainly related to DNA contributions. The most important ones are located at 1085 (PO_2^- symmetric stretching) and 1052 cm^{-1} (C–O stretching). In this region too, differences can be noted in the band shape. Additionally, the other structures positioned at 968 cm^{-1} (C–C stretching), 893 cm^{-1} (deoxyribose ring), 835 cm^{-1} (S-type sugar) are attributed to DNA. A complete list of the peak position and band assignments is reported in Table 1.

Table 1. Mode assignments for the FT-IR frequency values in caput and cauda sperm samples, abbreviation: as = asymmetric, s = symmetric, ν = stretching, vbr = vibration, b = bending, scis = scissoring.

Peak *caput* **cm^{-1}**	**Peak *cauda*** **cm^{-1}**	**Peak Assignments**	**Biochemical Molecules**
3400	3395	Hydrogen bonded O-H N-H	protein water
3309	3290	Amide A N-H	protein
3013	3013	olefinic = C-H	unsaturated lipid
2957	2959	CH_3 as	lipid
2922	2924	CH_2 as	lipid
2875	2875	CH_3 s	lipid
2851	2853	CH_2 s	lipid
1654	1654	Amide I-helix	protein
1648	1648	Amide I	protein
1540	1547	Amide II	protein
1455	1456	CH_3 as b CH_2 scis	lipid and protein
1395	1395	COO- s	fatty acid
1300	1300	Amide III	protein
1230	1230	PO_2- as	nucleic acids and phospholipids
1171	1171	CO-O-C	glycogen
1085	1085	PO_2- s	nucleic acids
1052	1052	C-O	saccharides and DNA deoxyribose
968	968	C-C	DNA backbone
893	893	Deoxyribose ring	DNA
835	835	DNA S-type sugar	DNA

4. Conclusions

The results reported here indicate that μFT-IR spectroscopy can constitute a useful tool for investigated changes occurring in SPZ from *caput* and *cauda* epididymis of mice in a rapid and easy way. Biochemical changes in protein, nucleic acid, lipid, and carbohydrate content of cells have been evidenced. Further work is in progress in order to quantitatively assess the observed differences.

Acknowledgments: This work was supported by Università della Campania "L. Vanvitelli" (Italy) under the project "Ricerca Scientifica di Dipartimento" (2017). The authors are pleased to thank Nadia Diano for useful discussions.

Conflicts of Interest: The authors declare that there is no conflict of interest.

Compliance with Ethical Standards: All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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