ICTAM 2016
MONTRÉAL

24th International Congress of Theoretical and Applied Mechanics

Palais des congrès, Montréal, Canada

August 21 – 26, 2016

Book of Papers

IUTAM International Union of Theoretical and Applied Mechanics
Official IUTAM Congress

www.ictam2016.org

Preface

This volume contains all ICTAM 2016 Papers presented as:
- Plenary Lectures,
- Prize Lectures - Batchelor and Hill
- Sectional Lectures
- Mini-symposia presentations
- Thematic Session presentations, and
- Short Talk with Poster presentations.

The content of this book is available electronically only and will be archived on the IUTAM permanent site as follows:

ISBN: NR16-127/2016E-EPUB
Catalogue Number: 978-0-660-05459-9

Foreword

The organizers are proud to present the ICTAM2016 papers.

The electronic collection contains all submissions accepted for either oral or poster presentation as of July 8, 2016.

Papers received after this date, as well as those included here, can be accessed using the my*ICTAM2016* congress mobile app.

After the Congress itself all papers will be archived on the permanent IUTAM website.

We would like to thank all the members of the International Program Committee, for generating the content for such an inspiring scientific program. We would also like to acknowledge the tremendous work performed by the National Research Council of Canada and Legend Conference Planning for converting all our ideas into an actual Congress program.

Papers are presented as they were submitted. The organisers take no responsibility for the content language and errors in the texts.

The International Program Committee
ICTAM 2016
Montreal, Canada

GOLD

VirginiaTech
Invent the Future®

Department of Biomedical Engineering and Mechanics

SILVER

UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING

BRONZE

McMaster University
ENGINEERING

SPECIAL

WATERLOO | ENGINEERING

UNIVERSITÉ Concordia UNIVERSITY

2016 BATCHELOR PRIZE Journal of Fluid Mechanics

ELSEVIER

Pacific Institute for the Mathematical Sciences

CANADIAN CONGRESS FOR APPLIED MECHANICS CANCAM CONGRÈS CANADIEN DE MÉCANIQUE APPLIQUÉE

uOttawa Faculté de génie Faculty of Engineering

McGill

Western Engineering

FACETS

Canada

NRC·CNRC

Index Codes

Opening Lecture:

OL

Closing Lectures:

CL

Batchelor Prize Lecture

BP

Hill Prize Lecture

HP

Sectional Lectures

SLnn-x

nn= Topic

-x= order of the lecture within topic

Thematic Sessions (Orals)

TS.FMxx-x.mm

TS = Presentation Type

MSxx/FMxx/SMxx/FSxx = Thematic Session and topic

-x = block order within session

.mm = speaking order within block

Short Talks with Poster

PO.MSxx-x.mm.xxx

PO = Presentation Type

MSxx/FMxx/SMxx/FSxx = Thematic Session and topic

-x = block order within session

.mm = speaking order within block

xxx = Board #

Table of Contents

ZONA PELUCIDA AS A MECHANO-RESPONSIVE POLYMER

Andjelka Hedrih[1] [a)]
[1] *Department for Biomedical Science, State University of Novi Pazar, Serbia*

Summary Zona pelucida (ZP) is the most outer structure of mammalian oocytes and is important for gamete recognition, fertilization and integrity of the embryo. ZP is highly sulfated and glycosylated polymer gel that exhibit visco-elastic properties. Temperature, pH, ionic strength influences its biological function and aggregate state. We consider ZP as mechano-responsive polymer and proposed a new theory of fertilization based on coupled chemical—electrical fields and modeled ZP as a non-linear oscillatory reactive system. Analysis of its oscillatory states regarding external force is discussed.

INTRODUCTION

The ZP can be considered as an oscillatory structure that exhibits transition in oscillatory behavior before and after fertilization [1, 2, 3]. Fertilization is a process of reunion of a single oocyte and single sperm cell. The process requires certain amount of functionally capable spermatozooa, although only one sperm will fertilized the oocyte ensuring the constant quantity of genetic material in each generation. In in vivo conditions there are constant decline of sperm number from the moment when they enter the female reproductive tract. In *in vitro* conditions the huge amount of spermatozooa are also required, partially due to huge differences in cell masses between spermatozoa and oocyte (in range of 10^7). In this system oocyte is reacting as inert body. Fertilization on the cellular level begins with receptor recognition but still some details of the fertilization process remain unknown. From the oscillatory theory of fertilzation [4] ZP changes its oscillatory states after fertilization [1, 2] as well as mechanical properties [4]. Changing in mechanical and electrical properties after fertilization allows attaching of silicon nano chip [5]. ZP is a polymer with highly sulfated glycoproteins interconnected with non covalent bonds, so it is easily dissolved by mild heating, low pH, low ionic strength [6].

BASIC CONCEPT OF THE MODEL

In this model ZP is considered as a mechano-responceive but also electroactive – polymer analog to [7, 8]. Using phenomenological mapping [9,10], concept of controlling chemical oscillations in mechano reactive gels [11,12] and consequent rhythmical soluble-insoluble changes of the gel [13] the new mechano-chemical fertilization concept is proposed. The system (ZP) is considered to be incompressible.

Oscillations in chemical reactions are possible to control via mechanical strain [11, 12].

Basic assumptions: Sperm penetration area is determined by local parameters acting upon ZP surface. ZP surface is negatively charged due to content of sulfated glycoproteins. Numerous sperms with different velocities and different sperm impact angles act upon ZP surface in a form of periodic impulsive forces transferring a part of their kinetic energy to the ZP structure. This external mechanical influence (time dependent force intensity and pressure changings) of spermatozoa cause changing in chemical reaction (analog to [11,12] that change local pH of ZP causing local changes of its aggregate state (analog to [13]) from solubile to insoluble or causing the state of plastic flow of ZP. The area of ZP where the plastic flow persists long enough will be the “week spot/area” for sperm penetration. The spermatozoon that is in range of this area could easily swim trough ZP. By changing the local parameters of external mechanical force (stress intensity, pressure, sperm arrangement…) it is possible to control local chemical oscillatory processes [11]. Further, receptor recognition between sperm and oocyte changes locale potential of cell membranes. According to proposed model of fertilization process, ZP has area of coupled mechano-elekttro-chemical fields. The approximation is that this phenomenon has a local character and that it is not uniform through the entire ZP.

Figure 1.Part of the oocyte with a. spermatozoa acting upon ZP b. Changing the local electro-mechanical properties of ZP c. Sperm penetration in the area of local change of aggregate stat. CG-cortical granules. Co-cytoplasm of the oocyte.

The changes of oscillatory states of ZP as a gel polymer could be described by gel energy density. The gel energy density could be described by equation:

$$u = u_{el} + u_{FH} + u_{ion} \tag{1}$$

Where u_{el} is rubber elasticity of cross linked polymer chains contribution to the gel energy density, u_{FH} -contribution from interaction between the polymer and solvent units, u_{ion} - contribution to gel energy density that comes from ions [9].
The basic equation that couples mechanical stress and strain in ZP polymer could be in form:

a) Corresponding author. Email: handjelka@hm.co.rs

$$\hat{\sigma} = -P(\phi)\hat{I} + c_0 v_0 \phi_0^{-1} \phi \hat{B} \tag{2}$$

Where $\hat{\sigma}$ is stress tensor, $P(\phi)$ -pressure, $\hat{I}$ - is unit tensor, c_0 - crosslink density-the number density of elastic strands in undeformed polymer network, v_0-velocity of the polymer network at the given network deformation, ϕ_0 -volume fraction of the polymer, ϕ , $\hat{B}$ -strain tensor in the swollen polymer gel. (taken from [9]). When the “chosen spermatozoa” swim through ZP, and its plasma membrane merge with oocyte plasma membrane, oocyte plasma membrane change its electrical potential and the cortical granules (CG) release will occur. According to the biochemical theory CG release is followed by structural changes and changes of mechanical properties of ZP resulting in polyspermy block. The exact roles of the content of CG are still not known. In light of coupled field theory we suggest possible role of CG: content of CG (mostly enzymes) are acting like catalyst to chemical reactions in sense they change pH of the local environment. Changed pH than change the conformation of the ZP glycoproteins and disclosed additional bounding sides on ZP glycoproteins leading to its structural reorganization.

CONCLUSIONS

Using mathematical analogies and phenomenological mapping ZP was considered as an responsive gel that respond on external mechano-electrical stimuli that originate of numerous spermatozoa impacting its surface in process of fertilization. Oscillatory changing of external mechano-electrical stimuli upon ZP surface lead to local oscillatory phenomenon of rhythmical soluble-insoluble changes of ZP resulting in sperm spermatozoa penetration via mechanism of oscillations of relaxation if the soluble ZP state lasts long enough. Local chemical oscillations of ZP gel could be control via external mechanical strain. The proposed model brings new light to understanding the process of fertilization.

Acknowledgments: Part of this research was supported by the Ministry of Education, Sciences and Technology of Republic of Serbia Grant ON174001, coordinated through Mathematical Institute SANU and realized through State University of NoviPazar.

References

[1] Hedrih A. Transition in oscillatory behavior in mouse oocyte and mouse embryo trough oscillatory spherical net model of mouse Zona Pellucida" ch in *Applied Non-Linear Dynamical Systems*, Springer Proceedings in Mathematics & Statistics 93, J. Awrejcewicz (ed.), **93**: 295-303. Springer International Publishing Switzerland, 2014.

[2] Hedrih A. Modeling oscillations of zona pelucida before and after fertilization EUROMECH Newsletter, Young Scientist Prize Paper. ENOC 2011 Young Scientist Prize, awarded at the 7th European Nonlinear Dynamics Conference held in Rome, Italy, July, 2011. Europian Mechanics Society, 40, pp. 6-14.

[3] Hedrih A. Frequency analysis of knot mass particles in oscillatory spherical net model of mouse *zona pellucida*. Lecture Session, Short Paper, Abstract book of 23rd IUTAM ICTAM Beijing 2012, SM01-049, pp. 209. ISBN 978-988-16022-3-7

[4] Murayama Y., Mizuno J., Kamakura H., Fueta Y,, Nakamura H., Akaishi K., Anzai K., Watanabe A., Inui H., Omata S. Mouse zona pellucida dynamically changes its elasticity during oocyte maturation, fertilization and early embryo development. *Human Cell* **19**:119–125, 2006.

[5] Durán, S. et al. Silicon-nanowire based attachment of silicon chips for mouse embryo labelling. *Lab Chip* **15**:1508–1514, 2015.

[6] Wasserman P. Zona Pellucida Glycoproteins. *Ann Rev Biochem* 57:415-442 1988.

[7] Hara Y. Function and Autonomous Behavior of Self-Oscillating Polymer Systems. *Polymers* **6:**1958-1971, 2014.

[8] Yashin V.V., and Balazs C.A. Pattern Formation and Shape Changes in Self-Oscillating Polymer Gels. *Science* 314: 798, 2006.

[9] (Stevanović) Hedrih R.K., Hedrih A.N. Phenomenological mapping and dynamical absorptions in chain systems with multiple degrees of freedom. *J Vib Cont* **22(1):**18–36, 2016.

[10] Hedrih N.A., Machado J.T., (Stevanović) Hedrih R. K. Electromechanical analogy and generalized function of fractional order energy dissipation in spherical net discrete continuum model of mouse zona pelucida. Proceedings of 5th International Congress of Serbian Society of Mechanics, Jun15-17th 2015, Arandjelovac, Serbia. Published by Serbian Society of Mechanics and Faculty of Technical Sciences Novi Sad, Editors: Spasić T.D, Lazarević M, Grahovac N, Žigić M. ISBN 978-86-7892-715-7, COBISS.SR-ID 296997639.

[11] Yashin V.V., Kuksenok O., Dayal P., Balazs A.C. Mechano-chemical oscillations and waves in reactive gels. *Rep Prog Phys*. 75: 6, 066601, 2012. doi: 10.1088/0034-4885/75/6/066601.

[12] Yashin, V.V., Van Vliet K.J., and Balazs, C.A. Controlling chemical oscillations in heterogeneous Belousov-Zhabotinsky gels via mechanical strain. *Physical Review E* 79 (2009), 046214 _2009.

[13] Yoshida R., Sakai T., Ito S., Yamaguchi T. Self-Oscillation of Polymer Chains with Rhythmical Soluble-Insoluble Changes. *J Am Chem Soc*. 124:8095-8098 9 8095, 2002.