INSTITUTE OF CYTOLOGY AND GENETICS
The Siberian Division of the Russian Academy of Sciences

INRA

Unité MIA Jouy-en-Josas
Mathématiques et Informatique Appliquées

SPS SACLAY PLANT SCIENCES

COMSOL CONFERENCE ROTTERDAM2013

Modeling Plant Morphodynamics in Predefined COMSOL Multiphysics® Interface

S. Nikolaev(1*), J.-C. Palauqui(2), A. Trubuil (3*)

1. Institute of cytology and genetics SB RAS, Novosibirsk ; 2. Institut Jean-Pierre Bourgin, INRA Versailles ; * Contact informations : nikolaev@bionet.nsc.ru; alain.trubuil@jouy.inra.fr;
3. Mathématiques et Informatique Appliquées, INRA Jouy en Josas

Abstract

We used predefined COMSOL interface to imitate biological growth and shape change (morphodynamics). We found a set of parameters that supply observed morphodynamics for Arabidopsis embryo during its transition from globular to heart stage.

Biological background, question of the study, and some hypothesis

What are growth and morphodynamics

Change of form of an organism (morphodynamics) takes place during growth as result of different growth rates of its parts. The growth can be considered as intercalation of “new” material particles between “old” ones. Such inhomogeneous intercalation (growth) results in deformation of different parts depending on mechanical properties of biological material. This deformation is observable as morphodynamics.
In this work we study morphodynamics of whole embryo during its development (fig.1).

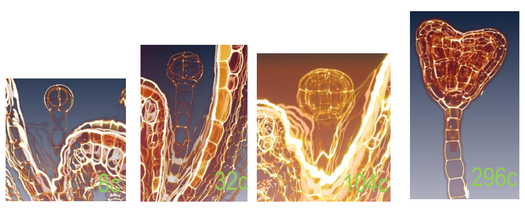

Fig.1. Embryos from early stage to drermatogen, globular and heart stage. Obsevations of walls revealed by IP and imaged in confocal microscopy.

Tissue-scale modeling

In this work we are especially interested in morphodynamics during embryo transition from globular form to “heart-similar” form.
We used confocal scanning microscopy, image processing, and geometry reconstruction to obtain partial information on growth distribution (Fig.2).

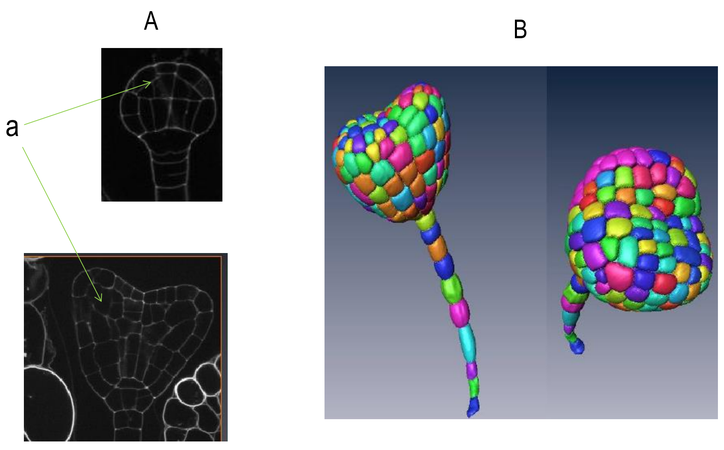

Fig.2. (A) Globular and heart forms of developing embryo: (a) - the domains are supposed to grow more intensively. (B) Bilateral symmetry of reconstructed 3D embryo.

The question of the study

What is growth distribution in the embryo that could result in an observed morphodynamics with given material properties of biological system.

Hypothesis:

From the images we proposed that regions ”a” (fig. 2A) grow more than other ones. Because there are images of longitudinal sections on the pictures, we assume the domain of intensive growth has a conical form.
Based on the fact that the apical part of the embryo looses cylindrical symmetry, and acquires bilatelal symmetry (fig. 2B), we supposed that the conical domain is modified by composition with a function having bilateral symmetry in the plane orthogonal to longitudinal axis.
So, we supposed a special distribution of growth rate inside the embryo.
And, finally, we supposed the growth and mechanical properties of embryo tissues are isotropic. This is that here we tested very simplified hypothesis.

Modeling in COMSOL

To solve the formulated question of the study one has not to develop a mechanistic (biophysically adequate) model of growth – it could be sufficient to imitate it. To do it we used evident similarity between volume increase by intercalation and volume increase by heating – in the both cases distances between “old” material particles increase [**1**,**2**].
To specify growth model using Physics Interface for Structural Mechanics / Thermal Stress we interpreted $\alpha \cdot \vartheta$ as growth tensor ε_g in $s = s_0 + C:(\varepsilon - \varepsilon_0 - \alpha \cdot \theta)$. So, when $\varepsilon_g = \varepsilon$, observing deformation is without stress - that is deformation by growth.

We model embryo at globular stage as a sphere with three layers: an external layer represents embryo epidermis (domain 1, E1=1e6[Pa]) , the most internal part (domain 4, E4=5e6[Pa]) is slowly growing part with high stiffness, and the layer between them (domain 2, E2=1e6[Pa]) that can grow more intensively.

To set up value for growth tensor we used controlled heat source to get predefined temperature distribution, and consider material as media without thermal conductivity. The last allowed us to specify growth distribution as we want.
In the simplest case that is presented here we used a uniform distribution of temperature by setting Heat Source Q=qt*(T-tt1) [], where qt=1.0[W/(m^3*K)], and tt1=274[K] are defined in Global Definitions/Parameters.

Inhomogeneous distribution of temperature was realized by setting special distribution of Heat capacity. Namely, the formulated hypotheses on growth distribution were formalized with the next functions:
We set maximal growth on conical surface with $\theta = 45^{\circ}$ in spherical coordinates with distribution as $Theta(r,\theta,\varphi) = sin^4(2\theta), 0 \le \theta \le \frac{\pi}{2}$;
We modulate the upper function with function $Phi(r,\varphi,z) = sin^2(\varphi)$ in cylindrical coordinates.

We defined these functions in Definitions/Variables in Material coordinates as $\left(Z > 0\right)\left(2Z\sqrt{X^2+Y^2}/(X^2+Y^2+Z^2)\right)^4$, and $\left(Z > 0\right)\left(X/\sqrt{X^2+Y^2}\right)^2$, where X,Y,Z – Cartesian coordinates. The functions are illustrated in fig. 3.

And finally we defined coefficients of thermal expansion as
0.04*(1+10*tphi*Theta)*Phi - for domain 1,
0.08*(1+12*tphi*Theta)*Phi - for domain 2,
0.01 - for domain 3, and 0.2 - for domain 4; and interpreted these as specific growth rates of the domains.

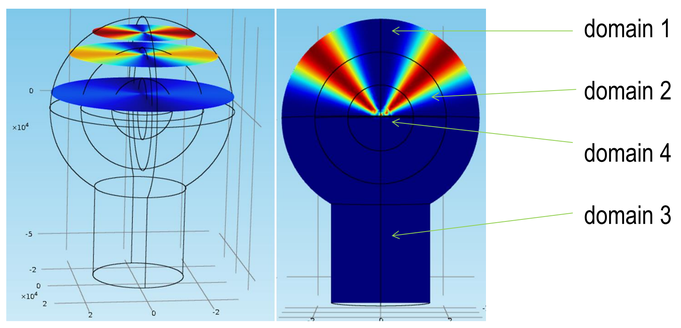

Fig.3. A model of globular stage of embryo. On left - crossections of a function *Phi*. On right - longitudinal section of function *Theta*.

Results

We found specific growth for different parts of the embryo to reproduce observable transition from globular to heart stage for Arabidopsis plant embryo by ascribing (fig. 4).

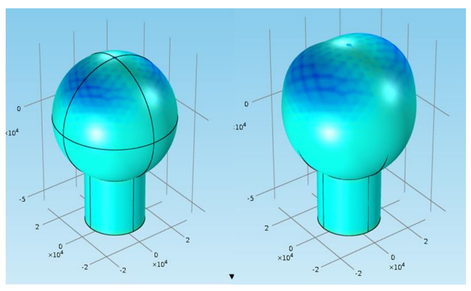

Fig.4. Initial (left), and final (right) shapes of morphodynamics calculation.

Increase of resulting volume is more in intermedial part of embryo as in external domain (fig. 5 A). In this case internal layer is stressed, and external one is stretched (fig. 5 B). This is because of more intensive growth of intermedial part of embryo.

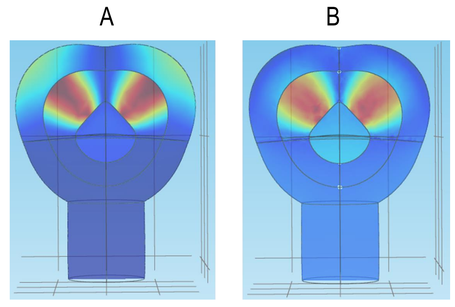

Fig. 5. Longitudinal sections of specific volume increase (left), and stress (right) distributions in deformed globular embryo. The final geometry has a heart-similar form.

Discussion

In this work we used simple elastic materials to model cell and tissue finite deformations during its morphodynamics. It is not correct because of visco-elasto-plasticity of cell walls and tissues, so the results can be considered only as a preliminary. Nevertheless, some qualitative conclusions can be made. A specific growth rate distribution can result in directed growth with isotropic local growth. Next, three-layered model of embryo with specified distribution of rigidities and growth rates demonstrates stretching of external layer and stressing of internal one, that was observed, for example, in meristem. Correctness of the elastic model can be improved by division of this one-step calculation into some smaller steps, with relaxations of intermediate forms.
Using Material coordinates is interpreted as the follows. The defined initial distribution of growth rate is initiated in globular stage of embryo development, and is succeeded by the cells derived from the initial ones.

Conclusion and perspectives

The work demonstrates a simple and useful way to model growth phenomena, and to study mechanical aspects of plant morphodynamics by using predefined COMSOL interface. It could be applied to other problems in plant or animal development biology Another advance could be to use geometries built on real image stacks, and imported into COMSOL [**3**] . This could be useful to many purposes, including parameter estimation.
It is well-known that mechanical behaviour of biological materials on different scales from macromolecules to organisms is very complex. These objects can demonstrate all “classical” deformations from elastic to plastic, and different combination of these ones including viscosity. Moreover, this mechanics can include an active component, and demand some complex model to describe stress-strain relations. And the COMSOL Multiphysics can be useful to catch this complex phenomena.

Acknowledgements:

S.N. is grateful to the Supercomputing center of the Novosibirsk state university for the opportunity to use COMSOL 4.3b; authors were partly supported by RFBR-INRA grant 11-04-91397-a, and RFBR grant 11–04–01748-a.

References:

[**1**] Volokh K.Y.., Mathematiical framework for modeling tissue growth, Biorheology 41, 263-269.
[**2**] Volokh, KY} A simple phenomenological theory of tissue growth Mech Chem Biosyst} 1, 2, 147-160, 2004.
[**3**] Nikolaev, S. et al, Modeling of plant embryo morphodynamics at early developmental stages, Russian Journal of Genetics: Applied Research, Vol 3, Num 3, 2013.