IUFoST 2006
DOI: 10.1051/IUFoST:20060228

Microscale modelling of gas diffusion in fruit tissue

Q. Tri Ho[1], H. K. Mebatsion[1], Fernando Mendoza[1], Bert E. Verlinden[1], Pieter Verboven[1], Stefan Vandewalle[2] and Bart M. Nicolaï[1]

[1]BIOSYST-MeBioS, Katholieke Universiteit Leuven, Willem de Croylaan 42, B-3001 Leuven, Belgium. quangtri.ho@biw.kuleuven.be

[2]Scientific Computing Research Group, Computer Science Dept., Katholieke Universiteit Leuven, Celestijnenlaan 200A, B-3001 Leuven, Belgium.

Abstract

Gas filled intercellular spaces are considered the predominant pathways for gas transport through plant organs and, as such, are greatly related to the characteristics of gas exchange. To understand the transport mechanisms of gas diffusion of fruit tissue, a microscale model for the transport of O_2 in the intercellular spaces, the cell wall network and the intracellular liquid phase was introduced. The objective of this study was (1) to verify the applicability of the microscale model of the gas transport at tissue level and (2) to quantify the pathways of gas transport in relation to the microstructure of fruit tissue. The 2D microstructure of pear tissue was modelled from light microscopy images using the ellipse tessellation method. Gas transport properties of the gas and liquid phases and the cell membrane were determined from available literature data. The O_2 transfer in each of intercellular space, cell wall and cytoplasm was applied using diffusion laws and irreversible thermodynamics. The model was solved using the finite element method. The results showed that the microscale model can be applied to study the gas transport in fruit tissue. The model quantified the pathways of gas transport in fruit tissue. The O_2 transport was mainly by means of the intercellular space, the cell wall network and less through the intracellular liquid. The results have important consequences for respiration–related disorders of fruits.

Key words: Microscale, gas transport, diffusion, tissue, modelling

Introduction

Micro structure of fruit tissue is complicated since it contains the cells connected together by the cell wall network and free spaces. At the fruit tissue level, O_2 is considered to transport by means of the intercellular space system and subsequently permeate through the cellular membrane to cellular solution. Finally, the O_2 diffuses within the cytoplasm to the centre of O_2 consumption while produced respiratory CO_2 follows the reversed path. Gas transport modeling at this microscale is needed to explain the gas behavior at tissue level.

In this contribution, a new approach for the detailed simulation of the O_2 transport in the fruit tissue was introduced using a microscale model. The objective of this contribution was (1) to verify the applicability of the microscale model of the gas transport at tissue level and (2) to quantify the pathways of gas transport in relation to the microstructure of fruit tissue.

Materials and methods

1. Model of gas transport in tissue

The microscale description includes mass transport of gas in (1) the intercellular space (pore), (2) the cell wall network, (3) the intra cellular space with respiration and (4) through the cell membrane. Fick' law of diffusion was applied for the gas transport:

$$\frac{\partial C_{O2,i}}{\partial t} = \nabla D_{O2,i} \nabla C_{O2,i} + R_i \qquad (1)$$

where $C_{O2,i}$ (mol/m^3) the O_2 concentration in phase i (i: pore, cell wall or intra-cell), ∇ (1/m) the gradient operator, $D_{O2,i}$ (m^2/s), the O_2 diffusivity of i, $R_{O2,i}$ (mol/m^{3}s) the O_2 consumption rate of i. O_2 transfer in the

Table 1 Model parameters

Model parameters	Value
Diffusivity	
-Pore*	1.6×10^{-5} m^2/s
-Cell*	2.01×10^{-9} m^2/s
-Cell wall	5×10^{-9} m^2/s
-Membrane**	2.91×10^{-10} m^2/s
Cell wall thickness	1μm
Cell membrane	8 nm
Henry constant of O_2*	1.37×10^{-2} (mol/m^{3}Pa)

* Lide (1999); ** Uchida (1992)

cell wall was considered in the gas phase. The O_2 concentration in the liquid intra cellular phase of intra cell was rewritten to equilibrate O_2 in the gas phase according Henry's law. The flux through membrane equals $J = -\frac{D_{O2,mem}}{L_{mem}}\Delta C$ (2)

where $D_{O2,mem}$ (m^2/s) and L_{mem} (m) are the O_2 diffusivity and thickness of cell membrane. ΔC (mol/m^3) is the concentration difference between membrane.

2. Geometry model and finite element solution

Pear tissue geometry was generated in 2D using ellipse tessellation algorithms (Mebatsion *et al.*, 2006). The geometry model was imported to Comsol Multiphysics (Comsol AB, Stockholm) and meshing was performed automatically by Comsol mesh generator resulting in 137462 triangular elements. The model equations (1) and (2) were solved using the finite element method.

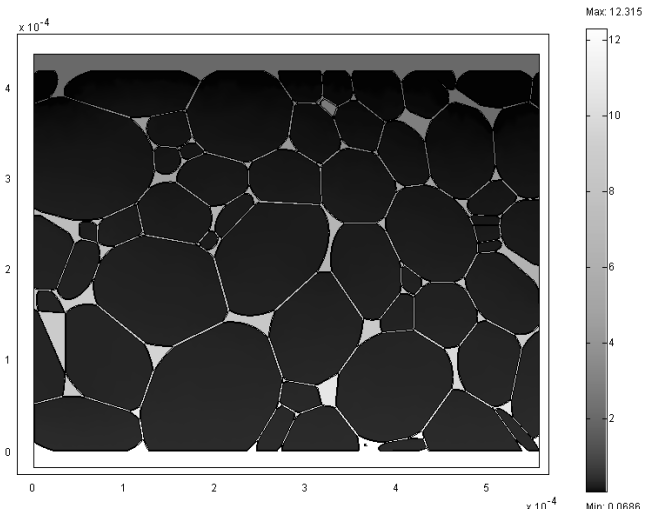

Figure 1 Modeled O_2 concentration in tissue

Results and discussions

The model was solved in steady state at 20°C in which 5 kPa and 30 kPa of O_2 were applied in two opposite boundary while the others were insulated. The O_2 consumption was considered to be constant ($R_{O2,tissue}$=2.26×10^{-4} mol/m^{3}s) at high O_2 partial pressure. The result shows that since the O_2 has low solubility in the cell (Henry's constant for O_2 at 20°C is 1.37×10^{-2} mol/m^{3}kPa), O_2 concentration was low inside the cells. Most of O_2 transfer occurred in the gas phase through the pores and the cell wall networks. Due to the very high diffusion of O_2 in the gas phase compared to diffusivity of the cell wall and cell, a uniform gas concentration of the gas in each pore domain was found. It was found that O_2 transfer mainly through the pore and cell wall of the tissue.

Conclusion

A microscale model was constructed for O_2 transfer through the intercellular spaces, cell wall and cytoplasm of tissue. The model quantified the pathways of gas transport in fruit tissue. The oxygen transport was mainly by means of the intercellular space, the cell wall network and less through the intracellular liquid. The results have important consequences for respiration–related disorders.

Acknowledgements

Financial support by the Flanders Fund for Scientific Research (FWO-Vlaanderen) (project G.0200.02) and the K.U.Leuven (project IDO/00/008 and OT 04/31, IRO PhD scholarship for Q.T. Ho) is gratefully acknowledged. Pieter Verboven is postdoctoral researcher of the Flemish Fund for Scientific Research (FWO-Vlaanderen).

References

Lide, D.R. 1999. Handbook of Chemistry and Physics. CRC Press, New York.

Mebatsion, H.K., Verboven, P., Ho, Q.T., Mendoza, F., Verlinden, B.E., Nguyen, T.A., Nicolaï, B.M., 2006. Modelling fruit microstructure using novel ellipse tessellation algorithm. Computer modeling in engineering & science, accepted.

Uchida, K., Matsuyama, K., Tanaka, K. and Doi, K., 1992. Diffusion coefficient for O_2 in plasma and mitochondrial membranes of rat cardiomyocytes. Respiration Physiology 90(3), 351-362.