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ВЕСТНИК

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NAS RK is pleased to announce that Bulletin of NAS RK scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of Bulletin of NAS RK in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential multidiscipline content to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабаршысы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Web of Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабаршысының Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді мультидисциплинарлы контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Вестник НАН РК» был принят для индексирования в Emerging Sources CitationIndex, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Вестника НАН РК в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному мультидисциплинарному контенту для нашего сообщества.

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3D NUMERICAL STUDY OF TEMPERATURE PATTERNS IN A FEMALE BREAST WITH TUMOR USING A REALISTIC MULTI-LAYERED MODEL

Abstract. This paper presents a three-dimensional numerical study of temperature patterns in a realistic multi-layered model of a female breast including blood perfusion. The breast surface temperature distributions are computed and analyzed with different tumor positions, sizes and different fat contents in the breast. The results are compared with experimental results for validation of the model. The paper shows that realistic breast model can accurately predict the temperature distributions inside the breast compared with traditional idealized models. The results demonstrate that all of the identifiable tumor occurrences were at the depth from 13 mm to 23 mm while none of the tumors at a depth of 29 mm were found to be detected. In respect to this, it was observed that tumors lied in the gland layer had less impact on the temperature profile of the breast. In addition, it was perceived that because of the natural deformation the breast geometry has an asymmetric surface temperature distribution in regards to symmetric tumor positions. Thus, the conducted parametric study analyzes the tumor location, size, and metabolic heat generation, and compares different temperature patterns subjected to the changes in the fat layer. Additionally, this study uses more realistic breast geometry model compared to previous studies. All this gives greater insight into the detectability of tumors with a variety of physiological conditions based on personalized patients' data and can give useful insight to improve the accuracy of computer-aided diagnosis using similar breast models. This can provide a very useful tool in inverse thermal modelling for the accurate detection of tumors in the breast.

Keywords: breast cancer, multilayer model, numerical study, fat content, COMSOL.

Introduction. Breast cancer is a multifactorial disease, the development of which is associated with changes in the genome of the cell under the influence of external causes and hormones. It is considered to be one of the most common diseases that lead to death among females. Early diagnosis is vital, as the tumor is highly treatable at the earlier stages [1].

There are many techniques for cancer diagnosis and the most common are breast examination and mammography. Thermography is another imaging technique using infrared rays to produce color pictures of the temperature distribution fields. According to Acharya et al. [2], the surface of a breast with cancerous tissues has higher temperature profile compared to the surrounding region and abnormalities can be discovered through thermography. A 0.5 °C difference in temperature profiles between two breasts of a patient is enough to conclude abnormal condition [1]. In Chen et al. [3], cameras with 0.1°C resolution with 4 second scan time can detect tumor hidden within more than one-third of the depth of the breast. Nowadays, thermography is capable of detecting possible tumor hidden inside more than one-fourth of the depth of a breast.

There have been numerous studies on the numerical analysis of female breasts with tumors. However, the studies used a simple model of the breast, whose geometry was assumed to be a perfect hemisphere which is axisymmetric. Only a small number of the studies considered multi-layered breast models to replicate realistic anatomy of the breast. Moreover, even the multi-layer models were assumed to have constant fat contents, which limits the information that can be gathered.

The main objective of this work is to examine temperature patterns generated by tumors on different locations based on multi-layered breast models with blood perfusion and different physiological conditions to provide insight into the detectability of tumor inside the breast. This study analyzes the tumor location, size, and metabolic heat generation, and compares different temperature patterns subjected to the changes in the fat layer. Additionally, this study uses more realistic breast geometry model compared to previous studies. The findings in this study could provide useful insight to improve the accuracy of computer-aided diagnosis using similar breast models.

1 Methodology of the study

To solve the steady-state thermal conduction problem in a breast, the bioheat equation presented by Pennes [4] was used in the model [5-9]: $k\nabla^2 T - c_b w_b \rho_b (T - T_a) + q_m = 0$, where “$k$” is the thermal conductivity; “c_b” is the heat capacity of blood; “w_b” is the blood perfusion coefficient; “ρ_b” is the density of the blood; “q_m” is the metabolic heat generation; “T” tissue temperature; “T_a” arterial temperature, which is equal to 37 °C, that is the same as the core temperature of the body.

At the boundaries, there are heat convection condition on the surface of the breast and the constant thoracic temperature condition applied at its bottom where it is connected to the thorax: $-k\,\Delta T = h(T - T_{ambient})$ and $T = T_a$, where $h = 13.5\ Wm^{-2\,0}C^{-1}$, which is evaluated for combined effects of convection, radiation and evaporation [10]. Equation (2) is a boundary condition at the skin surface representing heat convection between breast surface and the ambient environment assumed to be air temperature $T_\infty = 22\ ^{O}C$. Equation (3) is a boundary condition at the surfaces representing body core and it always remains constant $T_a = 37$ °C.

In order to consider a geometrically realistic breast as a 3D-model, the geometry obtained by Mukhmetov et. al. [11,12] was used as a base model (figure 1). The authors used an engineering scanning technique to obtain a 3D surface model of a mannequin chest and converted it into a solid breast model in SolidWorks CAD software. The overall geometry was not changed, but layers of materials were added to simulate real breast tissues. The parameters chosen were: height of the gland layer (figure 2), spherical coordinates (r, θ, φ in figures 3,4), of the center of the tumor inside the breast, and the diameter of the tumor, totaling five independent parameters.

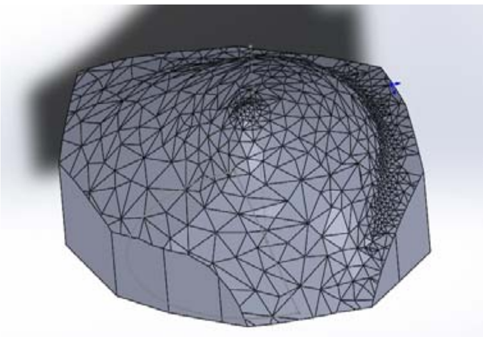


Figure 1 - The breast model developed by Mukhmetov [14]

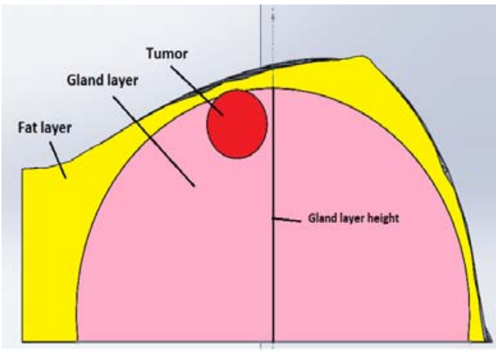


Figure 2 - A cross-section view of the 3D model of the breast in SolidWorks

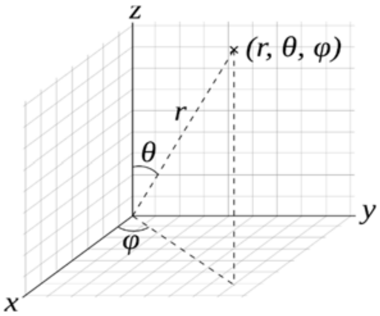


Figure 3 - Spherical coordinate system

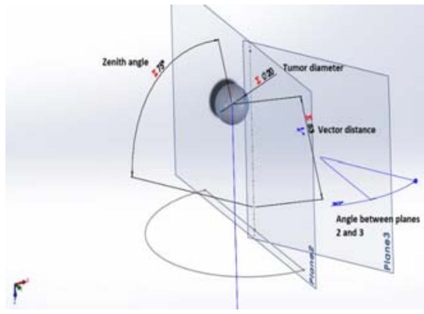


Figure 4 - CAD model in spherical coordinate

COMSOL Multiphysics was chosen as a solver because it includes bioheat transfer module [10], to synchronize 3D model changes between SolidWorks and COMSOL the "LiveLink". The "biological tissue" feature of the COMSOL was used to set the heat generation values for each tissue: fat, gland layer and tumor. The feature has dedicated settings for blood perfusion and metabolic heat generation terms. The domains and contact regions are automatically recognized by the COMSOL via LiveLink feature and can be easily selected for application of materials. The PARDISO was set as a solver with automatic preordering algorithm. Also, the nonlinear Newton method was used with initial damping factor of 0.01 and minimum damping factor of 10^{-6}.

The parameters of thermal properties for all the breast tissues were taken from Ng and Sudharsan [10] and are presented in table 1.

From Bezerra et. al. [6] the metabolic heat generation of the tumor can be derived from the function of Doubling time: $q_m * \tau = C\ (W * day/m^3)$, where *"C"* is a constant C=3.27×10^6 W×day/m^3 and "τ" is the doubling time value. On top of that, the tumor dimeter is a function of doubling time as [7]: $D = 0.01 * \exp\,(0.002134 * (\tau - 50))$.

Table 1 - Pennes equation parameters [10]

Parameter name	Symbol	Fat	Gland	Tumor
Thermal conductivity (W/mK)	k	0.21	0.42	0.42
Blood perfusion (ml/s/ml)	w	0.0002	0.0006	0.012
Density (kg/m^3)	ρ	920	1050	1060
Specific heat (J/kg K)	c	2770	3770	3800
Arterial temperature (°C)	T	37	37	37
Metabolic heat generation (W/m^3)	q	400	700	29000

From these equations, the heat generation can be estimated for each input diameter of the tumor, such as 10, 15 and 20 mm. The variation of this parameter would give insight into the relationship between detectability of tumor for various body fat values which normally vary with ages of patients. This parameter was varied as H_{gland} = 74, 64 and 54 mm which resulted in 36.7%, 49.4%, and 60.3% of fat content in the 3D breast model respectively.

These parameters were uploaded to COMSOL Multiphysics via option in "Parametric sweep" study. In order to have reference temperatures for comparison, several simulations were conducted for H_{gland} = 74, 64 and 54 mm (fat content of {36.7%, 49.4%, and 60.3%}) for the breast without a tumor.

3 Results and discussion

To ensure accurate and reliable result, a mesh convergence study was conducted and for this purpose tetrahedral mesh was adopted. Mesh convergence study was varied, ranging from 5,193 elements to 178,517 elements and the probe was placed at the center of the tumor that corresponds to the maximum temperature in the breast. Based on figure 5, it was decided to use 37,231 tetrahedral mesh elements due to the convergence of the results within the change of 0.002 °C, which is a much smaller value than the resolution of thermal cameras needed to identify tumor [1]. The difference in the number of elements is associated with the complexity of the realistic model.

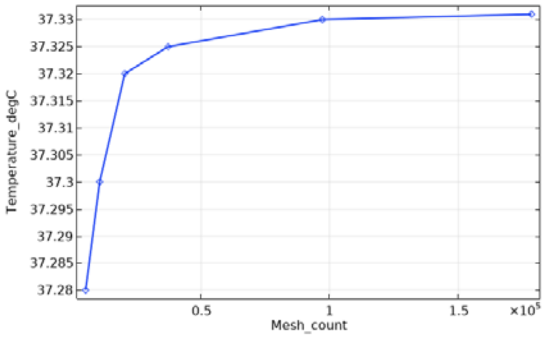


Figure 5 - Results of mesh verification study for a tumor of radius 20 mm, zenith angle of 90 mm, tumor distance of 54 mm, and a gland height of 74 mm

Based on the forward simulation of the heat conductivity in the breast without tumour for the values of gland layer height = {74, 64, 54} mm, the respective values of average surface temperatures are {304.084, 303.428, 303.175} K. The average temperature data indicates that the surface temperature is cooler with decreasing height of gland layer or increasing fat content. This trend is due to the change of material properties near the surface area, namely the increase of fat layer, which has lower metabolic heat generation rate as well as lower blood perfusion rate. Furthermore, surface temperature difference distributions between healthy (no tumor) breast and breast with tumor become less significant with decreasing vector distance (figure 6).

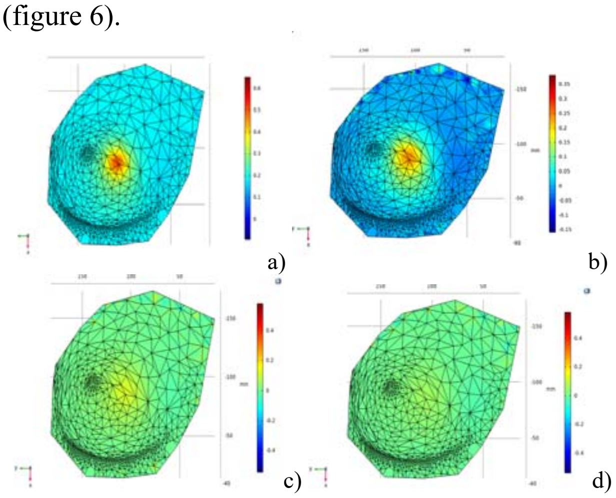


Figure 6 - The temperature difference distributions between diseased and healthy breasts for gland layer of 74mm, a tumor of 20mm, zenith angle of 90º, vector distance of: a) 54 mm; b) 49 mm; c) 44 mm; d) 39 mm and reference data of the same gland layer

Since the vectors distance is the distance from the center of spherical coordinates to the tumor center, decreasing vector distance means increasing tumor depth from the skin surface. Based on Figure 9*d*, the identification of tumor at depth of 29 mm is unlikely due to the fact that the maximum observed temperature difference was 0.058 ºC while according to the literature it should be at least 0.5 ºC [1]. Furthermore, changing the zenith angle to 60º results in the same pattern of tumor recognition features that fade away with deepening tumor location (figure 7) and gives a visual cue on the change of tumor position due to zenith angle.

Figure 8 represents a deviation of the surface temperature of the breast with a tumor from a reference breast. The threshold average surface temperature on the skin surface was calculated to be {0.0189 ºC}, which corresponds to the maximum surface temperature difference of 0.5 ºC between tumorous and reference breast model that was concluded as enough to identify a breast with a tumor [1]. This threshold was used to identify the detectable tumors from the parameter sweep data.

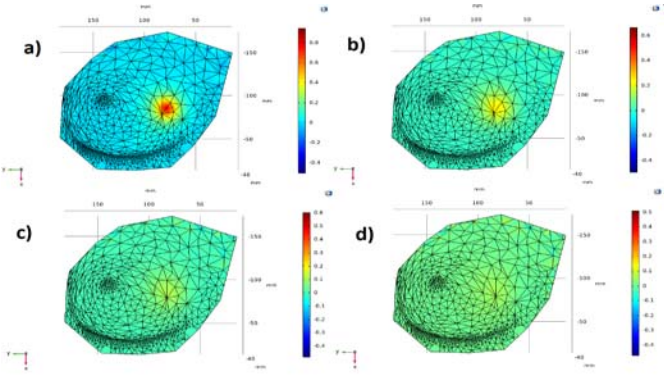


Figure 7 –
The temperature difference distributions
between diseased and healthy breast for gland layer
of 74 mm, a tumor of 15 mm, zenith angle of 60º,
vector distances of a) 54 mm, b) 49 mm, c) 44 mm,
d) 39 mm and reference data of the same gland layer

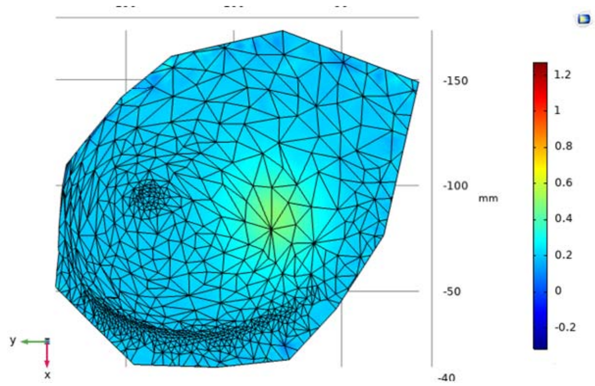


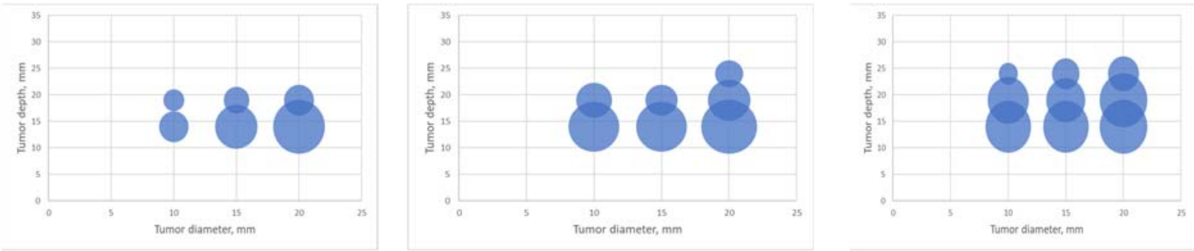
Figure 8 –
The surface temperature difference distribution
between cancerous and healthy breasts for gland layer
of 74 mm, a tumor of 20 mm, zenith angle of 60º, vector
distance of 49 mm and reference data of the same gland layer

Table 2 reveals a summary of the data obtained for analysis. The total number of simulations for each gland height case was 144: a combination of tumor diameters of {20, 15, 10} mm, zenith angle of {60º, 80º, 100º, 120º}, the angle between planes of {0º, 90º, 45º}, tumor depth of {14, 19, 24, 29} mm derived from vector distances of {54, 49, 44, 39} mm respectively. The table shows the number of simulations that surpassed the threshold of being detectable. The obvious trend is that the instances increase with decreasing gland height or increasing the fat content. This is due to lower metabolic heat generation, lower heat capacity, and lower blood diffusion coefficient of fat tissue that cannot contain the heat generated by the tumor and conducts it through generating a more distinct pattern compared to a thinner layer. Although this property of tumor detectability may indicate that people with more fat content can detect tumor easier, it should be taken with caution. The fact is that additional fat increases breast size and breasts with the same gland size but different fat content will have different overall size. If the tumor grows on the same place on the glandular tissue the tumor will be deeper from the surface for the breast with more fat content compared to another breast.

Table 2 - Number of instances categorized as detectable out of 12 for different gland layer height and fat content

Tumor depth, mm	Gland layer 74 mm; Fat content 36.7%			Gland layer 64 mm; Fat content 49.4%			Gland layer 54 mm; Fat content 60.3%		
	Tumor diameter, mm			Tumor diameter, mm			Tumor diameter, mm		
	20	15	10	20	15	10	20	15	10
14	12	8	4	12	10	10	12	11	11
19	4	3	2	7	4	5	12	8	9
24	0	0	0	3	0	0	5	4	2
29	0	0	0	0	0	0	0	0	0
Total			33			51			74

Figure 9 shows novel bubble charts of tumor detectability, which is found to increase with the tumor diameter. In addition, it should be noted that the data showed no occurrences of detectable tumor that had a depth of 29 mm, among all simulations. This depth puts the tumor inside the glandular tissue even at the highest fat content of 60.3%. The high heat capacity and high blood perfusion of the gland contained prevents identifiable hot spots on the surface of the breast model.



a) b) c)

Figure 9 - Scatter bubble chart for fat content of:
a) 36.7%; b) 49.4%; c) 60.3% where the size represents a number of detected instances

Moreover, at a gland height of 64 mm, the number of instances with 10 mm diameter tumor being detected is higher than the number of detected tumors with a 15 mm diameter. This was the result of sufficiently high heat generation rate of the 10 mm tumor as well as being fully located in the fat layer due to its smaller size that resulted in greater detectability of the tumor.

An interesting trend was observed when comparing data of zenith angles 60º and 120º of different plane angles. The pattern was that there was a difference between average temperatures of heat patterns produced by tumors at upper and lower regions on the breast with respect to the x-axis. The upper region is tumor locations with parameters: a zenith angle 60º and a plane angle of 90º, whereas lower region has a zenith angle of 120º and a plane angle of 90º. The average temperatures were compared and the upper region generated 20.785% more heat on average. This asymmetry could be explained by the fact that the realistic geometry of the breast that was used in this study is asymmetric due to natural deformation of the breast under the effect of gravity and lower part of the breast has accumulated tissue which creates asymmetry in final surface temperatures. This effect was impossible to observe in previous studies that assumed the breast to be perfectly semispherical and thus axisymmetric. Further examination was done on the comparison between the left and rights regions. The right tumor locations could be described by the parameters: a zenith angle 60º and a plane angle of 0º, whereas the left region has a zenith angle of 120º and a plane angle of 0º. A similar comparison was performed and the difference in the surface temperatures was 7.157% on average. This suggests that the tumors that are located in the lower regions are harder to identify compared to upper regions and that left and right temperature profiles vary less than the top and bottom temperature profiles.

Conclusion. A sophisticated 3D numerical heat transfer model for the breast was developed and validated. Selected breasts were simulated by the model with various sized tumors and corresponding metabolic heat generation rates, different locations of the tumor and gland heights that corresponded to fat content. The predicted temperature agreed well with experimental results from the studies of Gautherie. The surface temperature was observed to be lower with increasing fat content, which could be estimated based on the thermogram using reverse thermal modeling. The parametric analysis of different tumor locations indicated that the variation of the surface temperature patterns due to tumor positions in the fat or gland layer significantly differed. As the diameter of a tumor increased its detectability increased correspondingly. The tumors that were fully emerged in the gland layer due to very thin fat layer had a significantly lower surface impact and sometimes did not give enough thermal signature in the breast surface to make it identifiable. All of the identifiable tumor occurrences were at the depth from 13 mm to 23 mm while none of the tumors at a depth of 29 mm were found to be detected. Moreover, it was observed that a naturally deformed breast geometry results in asymmetric surface temperature distribution with respect to symmetric tumor positions. This behavior did not take place in the previous studies with axisymmetric breast models.

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ҮШӨЛШЕМДІ НАҚТЫ КӨПҚАБАТТЫ МОДЕЛЬДІ ҚОЛДАНУ АРҚЫЛЫ ІСІГІ БАР ӘЙЕЛ ОМЫРАУЫ БЕТІНДЕГІ ТЕМПЕРАТУРАНЫҢ ТАРАЛУЫН ЗЕРТТЕУ

Аннотация. Мақалада қан перфузиясын қоса алғандағы әйел омырауының реалистік көпқабатты моделінің нақты беткі қабатында температураның таралуы мен жылу өткізгіштігінің үшөлшемді математикалық зерттеулері көрсетілген. Сүт безі бетіндегі жылу өткізгіштік пен температураның таралуы әйел омырауындағы түрлі ісік позициясы, мөлшері және түрлі тығыздықпен (май мөлшері) есептеледі және талданады. Әйел омырауына арналған аталған модель дәстүрлі идеализацияланған модельдермен салыстырғанда омырау ішінде температураның таралуын дәл болжай алатындығы жұмыста көрсетілді. Есептеу нәтижелері барлық анықталған ісіктер 13 мм-ден 23 мм-ге дейінгі тереңдікте болатынын көрсетті. 29 мм және одан да арықарайғы тереңдіктегі ісіктер анықталмады. Сондықтан сүт безінің қабатында жатқан ісіктер сүт бездері бетінің жылу өткізгіштігіне және температурасының таралуына аз әсер ететіні атап өтілді. Сонымен қатар, зерттеулер, табиғи деформацияға байланысты әйел омырауының геометриясы, ісіктің симметриялы позицияларына қатысты беткі температураның асимметриялық таралатынын көрсетеді. Сөйтіп, өткізілген параметрлік және математикалық зерттеулер ісіктің шоғырлануын, мөлшерін және метаболикалық жылу бөлінісін талдайды. Сонымен қатар, айтылған зертеулер май қабатындағы өзгерістерге ұшырайтын түрлі температуралық заңдылықтарды салыстырады. Мұның бәрі пациенттердің жеке деректері негізінде түрлі физиологиялық жағдайдағы ісіктерді анықтау туралы кеңірек түсінік береді және сүт бездерінің ұқсас модельдерін қолдану негізінде компьютер-лік диагностика дәлдігін жақсартуға пайдалы ақпарат ұсынады.

Түйін сөздер: сүт безінің қатерлі ісігі, көпқабатты модель, сандық зерттеу, май мөлшері, COMSOL.

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ЧИСЛЕННОЕ ИЗУЧЕНИЕ РАСПРЕДЕЛЕНИЯ ТЕМПЕРАТУРЫ НА ПОВЕРХНОСТИ ЖЕНСКОЙ ГРУДИ ПРИ НАЛИЧИИ ОПУХОЛИ С ИСПОЛЬЗОВАНИЕМ ТРЕХМЕРНОЙ РЕАЛИСТИЧЕСКОЙ МНОГОСЛОЙНОЙ МОДЕЛИ

Аннотация. В данной работе представлено трехмерное численное исследование температурных паттернов в реалистичной многослойной модели женской молочной железы, включая перфузию крови. Распределение температуры поверхности молочной железы вычисляется и анализируется при различных положениях опухоли, размерах и различном содержании жира в молочной железе. Полученные результаты сравниваются с экспериментальными результатами для валидации модели. В статье показано, что реалистичная модель груди может точно предсказать распределение температуры внутри груди по сравнению с традиционными идеализированными моделями. Результаты показывают, что все идентифицируемые опухолевые образования находились на глубине от 13 до 23 мм, в то время как ни одна из опухолей на глубине 29 мм не была обнаружена. В связи с этим было замечено, что опухоли, лежащие в слое железы, оказывали меньшее влияние на температурный профиль молочной железы. Кроме того, было замечено, что из-за естественной деформации геометрия груди имеет асимметричное распределение температуры поверхности относительно симметричных положений опухоли. Таким образом, проведенное параметрическое исследование анализирует локализацию опухоли, ее размеры и метаболическое тепловыделение, а также сравнивает различные температурные паттерны, подверженные изменениям жирового слоя. Кроме того, в этом исследовании используется более реалистичная геометрическая модель груди по сравнению с предыдущими исследованиями. Все это дает более глубокое понимание выявляемости опухолей с различными физиологическими состояниями на основе персонализированных данных пациентов и может дать полезную информацию для повышения точности компьютерной диагностики с использованием аналогичных моделей молочной железы. Это может стать очень полезным инструментом в обратном тепловом моделировании для точного обнаружения опухолей в молочной железе.

Ключевые слова: рак молочной железы, многослойная модель, численное исследование, содержание жира, COMSOL.

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