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Simulation of Over-Milking Process on Bovine Teat Applying Finite Element Method

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Özet

İnek Memesinde Aşırı Sağım İşleminin Sonlu Elemanlar Yöntemi Uygulamasıyla Simülasyonu

Bu çalışma, Sonlu Elemanlar Yöntemi'ne dayanan geniş kapsamlı bir araştırmanın temel nitelikteki birincil bulgularını içermektedir. Çalışmada, makinalı sağımda iki fazdan biri olan sağım fazı simüle edilmiş ve bu amaçla özel bir şirketten elde edilen yeni kesilmiş çok sayıda inek memeleri üzerinde boyut belirleme çalışması yapılmıştır. Bu memeler arasında tipik bir tanesi esas alınmış, görünüşü kağıt üzerinde çizilmiş ve buradan elde edilen iki boyuttaki koordinatlar bilgisayara girilmiştir. Marc adı verilen programda memenin belirli bir eksende simetrik olduğu düşünülerek yalnızca yarısı simüle edilmiştir. Simülasyonlarda ayrıca meme içerisinde sütün olmadığı varsayımı yapılmıştır. Bu varsayım ile çalışma aşırı sağımın simülasyonu şeklinde yürütülmüştür.

Gerekli sınır değer koşullarının ve meme elastik özelliklerinin tanımlanması sonucunda simüle edilen bir inek memesinde oluşan defomasyonlar ve gerilmeler elde edilmiştir. Çalışma sonucunda elde edilen bulgulara göre memede en kritik bölgelerden birisinin meme kanalı olduğu saptanmıştır.

Anahtar Sözcükler: Aşırı sağım, simülasyon, makinalı sağım, gerilme

Introduction

Milking is not an easy process as it is thought since many variables involve in this phenomena. These variables can be divided into two parts, machine and teat related variables. The most important machine related variables could be stated as the level of vacuum applied, pulsation characteristics, the liner properties and the age of the

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liner. The teat related variables could be the size and the stiffness of the teat. In addition to the main effect of these factors in milking, their interaction is of importance. One of the situations that occur in reality is the inharmonious action of a rubber liner and a teat. This will reduce the milking efficiency and will also cause a reduction in milk yield. Finally, this situation may also result in problems related to herd management.

Theoretically, milk within the teat acts as a cushion against the collapse of the teat liner and prevents frictional irritation to the epithelial lining of the teat cistern. Conversely, collapsing action of liners on empty teats is injurious (Peterson, 1964). The process of milking from empty teats is called over-milking and this situation usually occurs due to improper milking machine use and this is accepted to be the key factor in machine-induced mastitis. The effects of improper milking machine use on teat condition and mastitis incidence were stressed in many studies, mostly experimental and at this point the reader is referred to read these studies conducted by Peterson, 1964; Hamann, 1985; Ingalls, 2000; Mein *et al*., 2001; Hillerton *et al*., 2002; Mein *et al*., 2003 in order to have a better understanding of this phenomena.

In addition to the experimental studies, the simulation based studies, on the other hand, may help to understand how and where the deformations and critical stresses occur in a teat.

One of the simulation tools in engineering applications is Finite Element Method (FEM) and our literature search revealed that some studies conducted by Balthazar(1978) and Toth *et al.* (2000) used FEM. A recent study by Toth *et al.* (2002) was applied to milking problem to analyze milk and cleaning liquid flow computation while the study by Balthazar was conducted with 1970's computer technology and did not include various elasticity properties and loading conditions. Today's technology allows to make the computations faster and to investigate the many aspects of the phenomena deeply.

For this reason, a study was conducted and the objectives of this study were to investigate:

- variable linear elastic parameters of teats and,
- variable loading effects on stress distribution in a teat in milking phase during over-milking process.

Material and Method

In order to study the teat behavior under load, a teat in 60 mm long was modeled and meshed in the program called Marc*. For this purpose, excised teats obtained from a private company were investigated from the point of their dimensions. The scaled photos of the teats were taken and their 2-D drawings were sketched on paper and then the coordinates of an average size teat were obtained and defined in the program in 2-D. The 2-D meshed teat structure was then converted into 3-D for studying the teat behavior.

The photo of one of the excised teats and the 3-D view and the dimensions of the teat used for simulations are shown in Figure 1.

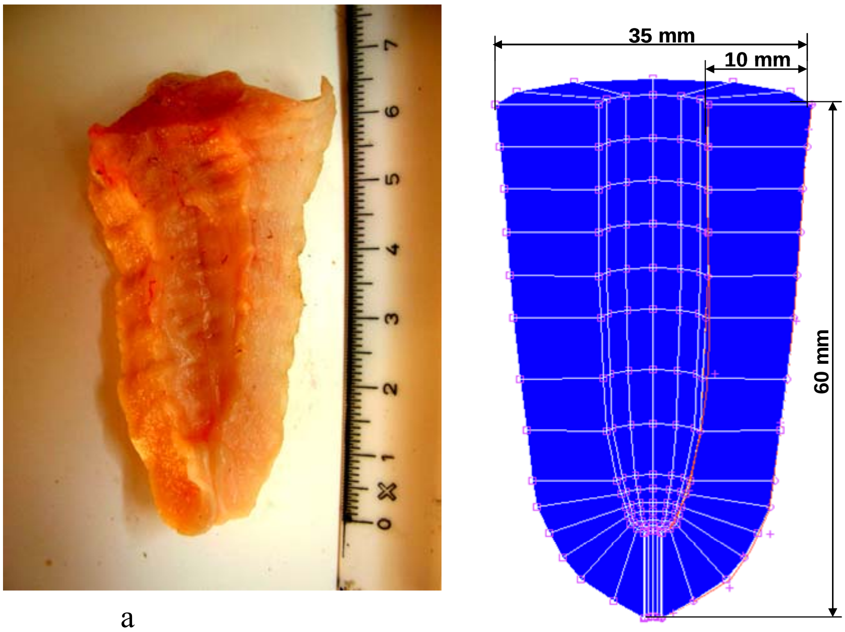

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Figure 1. a) General view of an excised teat, b) meshed view and dimensions of the teat simulated

The thickness of the teat wall was in the neighborhood of 10 mm. The diameter and the length of the teat canal were 1 and 10 mm, respectively. The modulus of elasticity (E) and Poisson's ratio (ν)

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values as stated by Davis *et al.* (2001) were used in simulations. The two values of modulus of elasticity (35 and 124 kPa) were selected. These are the minimum and maximum limits of the modulus of elasticity values given by Davis *et al.* (2001). Poisson's ratio was assumed to be 0.45 for the simulations and this was the minimum value reported by Davis *et al.* (2001).

Finite Element Formulation of the Problem

The finite element is a general method of structural analysis in which a continuous structure is replaced by a number of elements interconnected at a finite number of nodal points. This study uses the finite element method to obtain displacements and stresses to simulate teat behavior when subjected to vacuum or negative pressure. The problem was studied in 3-D that assumes that the applied loads lie in the x-y-z plane. The weight of the teatcup and teat were ignored for the simulations.

The finite element analysis (Zienkiewicz, O.C., R.L. Taylor, 1994) consists of the following basic operations;

1. Development of stiffness matrix of an arbitrary element with respect to local co-ordinate system,
2. Transformation of the element stiffness from the local co-ordinate system to a global co-ordinate system of the complete structural assemblage,
3. Superposition of individual element stiffness to obtain the total stiffness matrix of the total system,
4. Formulation of equilibrium equations relating the applied nodal forces and resulting nodal displacements and their solution,
5. Computation of element stresses resulting from the computed nodal displacements making use of the element stiffness matrices.

The 3-D shape of the teat modeled in the simulation program included 84 hexagonal elements associated with 504 nodes. Some assumptions were also made for the simulations. It was assumed that the teat is symmetrical around the longitudinal axis (y) and the whole teat has the same modulus of elasticity and Poisson's ratio.

The necessary boundary conditions assigned in order to carry out the over-milking simulation in teat are as follows.

The boundary conditions imposed were: the nodes on the top of the teat were fixed in x, y and z direction (BC1) while the nodes at the symmetrical axis were fixed in z direction only (BC2).

Face load was defined on the faces of the elements that surround the teat. The application of the face load was applied in order to simulate the milking phase only. The load was applied to the element phases as vacuum but this was carried out as vacuum pressure of 50 kPa to the bottom element phases (BC3). On the other hand, the element phases starting from the bottom 5 mm to the upper 45 mm was assumed to be subjected to a vacuum of 30 kPa (BC4).

Another combination of vacuum pressure was also assigned as 40 (BC3) and 20 kPa (BC4) to the teat in the same was as described above.

A variable loading case was also studied and this type of loading included the maximum vacuum of 50 kPa at the bottom and gradually decreasing to the top of the teat and ending with 30 kPa.

In the study, it was assumed that there exists no-milk in the teat for the sake of simplicity. As a result of this assumption, this study became the simulation of over-milking process.

Loading conditions and teat elastic properties used for the simulations are tabulated in Table 1.

Each loading case was simulated separately and from the simulations, the displacements and stresses were obtained. The peak values and their locus were also determined.

Table 1. Loading conditions used for simulations

Loading code	Loading conditions and material properties used
M5030E1	50 kPa Vacuum –bottom; 30 kPa Vacuum - upper E1=124 kPa ; ν=0.45
M5030E2	50 kPa Vacuum – bottom; 30 kPa Vacuum - upper E2=35 kPa; ν=0.45
M4020E1	40 kPa Vacuum –bottom; 20 kPa Vacuum - upper E1=124 kPa; ν=0.45
M4020E2	40 kPa Vacuum – bottom; 20 kPa Vacuum - upper E2=35 kPa; ν=0.45
MVE1	50 kPa Vacuum – bottom; Variable Vacuum - upper E1=124 kPa; ν=0.45
MVE2	50 kPa Vacuum – bottom; Variable Vacuum - upper E2=35 kPa; ν=0.45

Results and Discussion

The simulated behaviour of the teat was first examined in terms of the correctness of the model developed in the simulation program. For this reason, the study conducted by Pier *et al.* (1956) was used to compare the behaviour of the teat in milking phase. As seen from Figure 2, the radiograph and the simulated view of the teat in milking phase show similarities. At a certain point of the upper part, the teat makes a necking and the whole teat is also pulled downward when it is compared to massage phase view (Figure 2a). This means that the teat is displaced in longitudinal direction. During this phase, it is expected that the teat canal also enlarges and milk is pushed out of the teat canal.

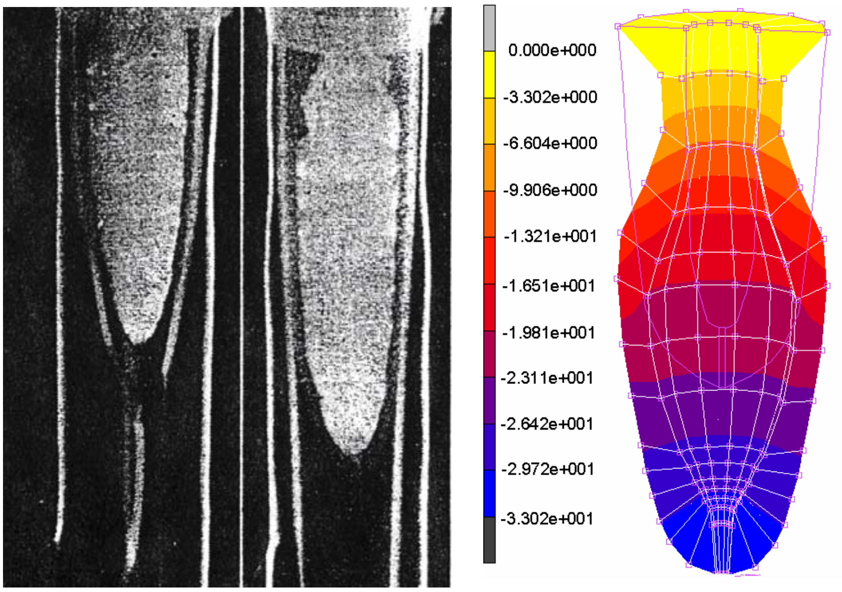

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Figure 2. Radiograph view of a teat (from Pier *et al*., 1956) in massage (a) and milking phase (b) and simulated displacements, mm (c) in longitudunal direction in teat in milking phase (E=35 kPa; variable loading case)

The correctness of simulation model for the teat behavior during milking phase can also be evaluated by examining Table 2. The displacements in teat canal in x direction mean how much the teat canal diameter enlarges. For example; for the loading case of M5030E1, the maximum displacement in teat canal is 0.29 mm. Considering the initial diameter of the teat canal of 1 mm, it could be stated that the final diameter of the teat canal for this case will be about 1.58 mm. The longitidunal displacements are the ones that indicate how much the teat moves downward or is pulled. For the same loading case the maximum displacement in longitudinal direction is 8.17 mm.

As seen from Table 2, the displacements in teat canal vary depending upon the loading condition and linear elastic value of the modulus of elasticity. The stifffer the teat is the smaller the displacements are. This result can be easily seen from Figure 3 and 4.

Table 2. Displacements in teat canal obtained from the simulations (mm)

Loading Code	x		y		z	
	Min	Max	Min	Max	Min	Max
M5030E1	0.21*	0.29**	-7.77	-8.17	-0.21	-0.29
M5030E2	0.75*	1.03**	-27.55	-28.95	-0.75	-1.03
M4020E1	0.19*	0.20**	-6.40	-6.75	-0.19	-0.20
M4020E2	0.70*	0.71**	-22.69	-23.94	-0.70	-0.71
MVE1	0.17*	0.35**	-10.2	-10.8	-0.17	-0.30
MVE2	0.62*	1.26**	-36.47	-38.29	-0.62	-1.26

*: Min values at lower part of the teat canal **: Max values at upper part of the teat canal

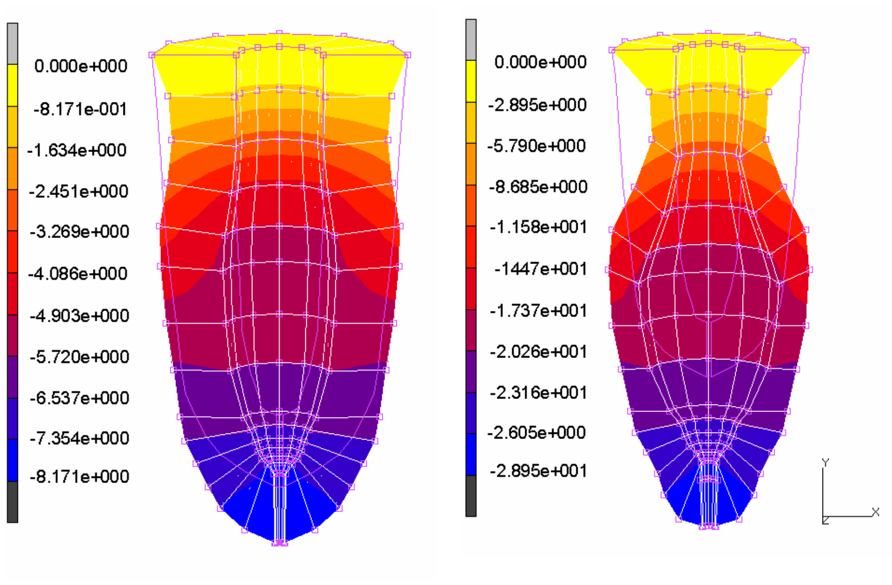

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Figure 3. Displacement contours in teat in longitudinal direction. Loading condition for a) M5030E1 and b) M5030E2; the scale on the left of each figure is in mm

The normal and shear stresses obtained from the simulations are given in Table 3 and 4, respectively. The findings in terms of normal and shear stresses in whole teat indicate that for the same loading condition, these stresses do not change as the modulus of elasticity was varied. But, under different loading conditions the values differentiated.

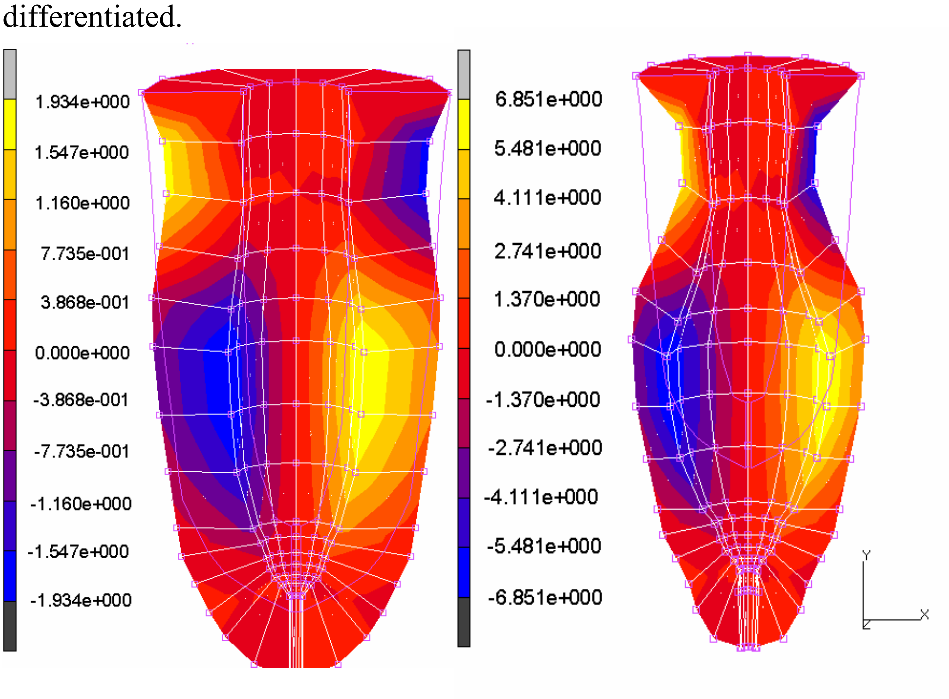

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Figure 4. Displacement contours in teat in lateral direction. Loading condition for a) M5030E1 and b) M5030E2; the scale on the left of each figure is in mm

Table 3. Normal stresses in teat (kPa)

Loading Code	σ_x		σ_y		σ_z	
	Min	Max	Min	Max	Min	Max
M5030E1	-2.23	68.11*	25.22	52.87	-6.73	68.43**
M5030E2	-2.22	68.11*	25.22	52.87	-6.73	68.43**
M4020E1	-1.66	55.01*	18.47	40.94	-4.65	51.90**
M4020E2	-1.66	55.01*	18.47	40.94	-4.65	51.90**
MVE1	-2.76	69.9*	28.78	52.75	-5.65	75.19**
MVE2	-2.76	69.9*	28.78	52.75	-5.65	75.19**

*: Max value in teat canal **: Max value at outer surface of the teat canal

Table 4. Shear stresses in teat (kPa)

Loading Code	τ_{xy}		τ_{xz}		τ_{yz}	
	Min	Max	Min	Max	Min	Max
M5030E1	-8.04	8.04	-7.84	7.84	-8.04	2.24
M5030E2	-8.04	8.04	-7.84	7.84	-8.04	2.24
M4020E1	-5.68	5.68	-5.16	5.16	-5.68	1.43
M4020E2	-5.68	5.68	-5.16	5.16	-5.68	1.43
MVE1	-7.69	7.69	-5.43	5.43	-7.69	9.28
MVE2	-7.69	7.69	-5.43	5.43	-7.69	9.28

The locus of maximum normal and shear stresses showed similarities even though the loading condition and the modulus of elasticity were changed. For example the maximum normal stress σ_x always occurred in teat canal.

The visual findings of stresses are depicted in Figure 5 and 6.

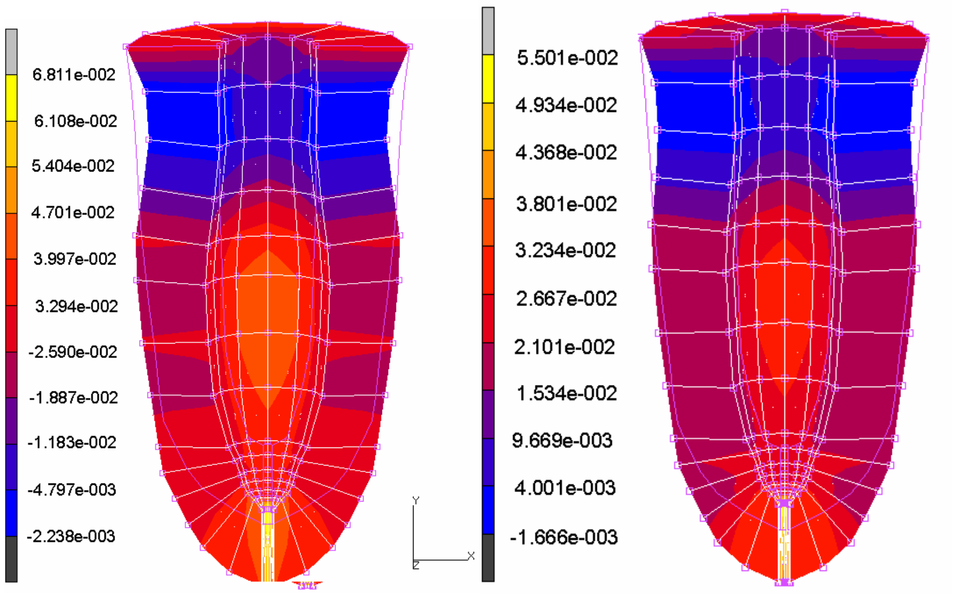

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Figure 5. Normal stresses (σ_x) contours in whole teat. Loading condition for a) M5030E1 and b) M4020E1 ; the scale on the left of each figure is in N mm^{-2}

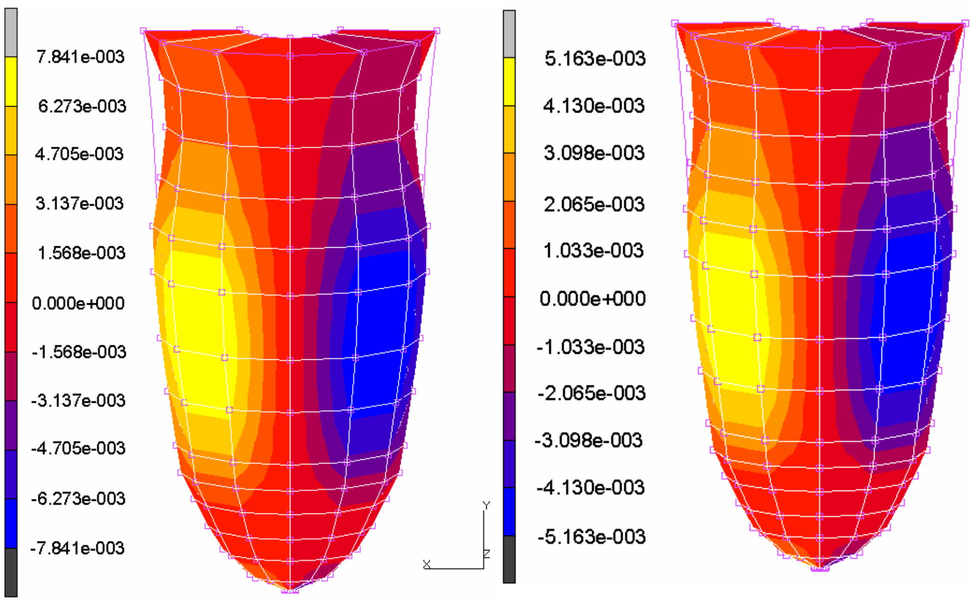

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Figure 6. Shear stresses (τ_{xz}) contours in whole teat. Loading condition for a) M5030E1 and b) M4020E1 ; the scale on the left of each figure is in N mm^{-2}

In general, the results obtained from this simulation based study indicated the teat canal is a critical point in terms of some normal and shear stresses once the teat is subjected to over milking. This result could be a good explanation how much an over milking process is injurious to a teat and also for the widespread use of automatic cluster removers since their use has significantly reduced over milking.

Conclusions

The following conclusions were drawn from the study:

1. The teat subjected to over-milking was modeled in 3-D and the behaviour of the teat under different loading conditions was verified by comparison with results of experiments.
2. When Modulus of elasticity was changed from 35 to 124 kPa, the displacements changed significantly but the stresses remained unchanged under the same loading conditions.
3. Different loading conditions changed both, the displacements and the level of stresses.

4. One of the critical points in teat is the teat canal. The maximum deformations and stresses may cause a damage in teat canal and this may result in an enviroment for the bacteria attack.
5. The maximum shear stresses occurring on the outer surface of the teat may be the cause of redness of the over-milked teat.

Future Studies

The authors of this study are currently studying various aspects of this phenomena in details such as the teat size effect, liner and teat interaction in milking and massage phases of pulsation. The differences with or without the existence of milk in teat will also be considered in future work. Experimental studies are also planned in order to compare the simulation results. It is expected that these studies will enhance the knowledge in machine milking effects on teat behaviour and may result in a better design of liners.

Summary

This is to reveal the preliminary findings of a comprehensive study based on Finite Element Method. In this study, teat behavior during milking phase was simulated and for this purpose, fresh excised teats were obtained from a private company and their dimensions were determined. A typical one among these teats was selected and its dimensions were measured and sketched out on paper. Only half of the teat was modeled assuming that the teat is symmetrical around longitudinal axis and meshed in a software called Marc. It was also assumed that there exists no-milk in teat. Under this assumption the study became the simulation of over-milking process from the teat.

The necessary boundary conditions to the teat were assigned, linear elastic behavior of the teat was simulated and information about deformations, strains and stresses resulted from the simulations were obtained. From the results obtained in the study, it was concluded that the apex of the teat (teat end) is one of the critical locations.

Keywords: Over-milking, simulation, machine milking, stress

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