Where $|\cdot|$ is the number of pixels in the respective set.

The SDNR per pixel of the inserted microcalcifications is defined as follows

$$SDNR = \frac{\langle SI_{back} \rangle - \langle SI_{\mu calc} \rangle}{\sigma_{back}}, \tag{5.4}$$

The SNR per background pixel was defined as follows

$$SNR = \frac{\langle SI_{back} \rangle}{\sigma_{back}}. \tag{5.5}$$

5.3.3 Average glandular dose

The estimation of the dose delivered to the glandular tissue remains an essential component of quality control in X-ray mammography. We derived the average glandular dose (AGD) using the approach proposed by Dance D. [31] regardless the paddle type. The method uses conversion factors to relate measurements of the incident air kerma K at the upper surface of the breast to the AGD.

$$AGD = Kgcs \tag{5.6}$$

where g is the factor allowing to convert air kerma to AGD considering a breast with 50% glandularity, c address any difference in breast composition from this 50% glandularity and s accounts for the X-ray spectrum under consideration. Dance D. et a. used Monte-Carlo simulation was used to estimate these factors by modeling the compressed breast as a semi-circular cross section cylinder. The s-factor for the recently introduced Rh/Ag target/filter spectrum was provided to us by D. Dance and has not been published yet.

The considered cross section cylinder has a uniform thickness, meanwhile the compressed breast thickness varies due to paddle elasticity (SRP) and paddle flexibility (SFP). Therefore, in a clinical framework, the breast thickness is adjusted by applying an offset characterizing the paddle deflection during compression.

For the rigid paddle model, as paddle elasticity was neglected, the AGD was computed assuming the breast thickness is equal to the distance between the image receptor and the paddle itself. Regarding the flex paddle, the breast thickness decreases quasi-linearly from the chest wall to the nipple. Thus, breast thickness was computed as the mean of the maximal and minimal distance over the breast contact area.

5.4 Results

Two studies were performed using the previously defined components for modeling the breast compression and simulating digital mammography. First, the results of a comparative study between flex and rigid paddles is presented with the effects on image quality, AGD and patient comfort. Then, the impact of paddle positioning on breast mechanics is analysed.

5.4.1 Compression quality for rigid and flex paddles

To compare the breast compression quality when using a standard rigid paddle against a standard flex paddle, the rigid and flex paddle models were used. The right breasts of the two volunteers were first compressed until the target breast thickness measured during mammography was obtained (Table 3.1). Then, the breast phantoms with $\mu calc$ were imported into CatSim environment and mammography images were simulated. The compression quality were measured in terms of image quality, AGD and patient comfort.

The resulting breast thickness after compression varies by less than $2mm$ between rigid and flex paddles for both volunteers (Table 5.10). Accordingly, small AGD difference was found and namely dose reductions of 2.6% for the smaller breast and 4.2% for the larger breast were observed in favor of the flex paddle.

x-ray

	Rigid Paddle		Flex Paddle		
	Mean SNR	StdDev SNR	Mean SNR	StdDev SNR	p-Values
Volunteer 1	82.90	43.09	83.70	37.72	0.706
Volunteer 2	126.89	8.75	137.21	10.73	0.000

Rigid Paddle		Flex Paddle	
BNT (mm)	AGD (mGy)	BNT (mm)	AGD (mGy)
46	1.15	44	1.12
48	1.20	46	1.15

	200 um					300 um				
	Rigid Paddle		Flex Paddle			Rigid Paddle		Flex Paddle		
	Mean SDNR	StdDev SDNR	Mean SDNR	StdDev SDNR	p-Values	Mean SDNR	StdDev SDNR	Mean SDNR	StdDev SDNR	p-Values
Volunteer 1	0.74	0.68	0.79	0.54	0.689	2.01	1.28	1.85	1.02	0.224
Volunteer 2	1.14	0.57	1.13	0.53	0.885	2.96	0.76	3.15	0.92	0.093

Figure 5.10: Breast nominal thickness (BNT), average glandular dose (AGD), signal-to-noise-ratio (SNR) and signal-difference-to-noise (SDNR) for both volunteers and both compression paddle types

The SNR and SDNR have been estimated and compared between flex and rigid paddles. When using a flex paddle instead of a rigid paddle on the largest breast (volunteer 2), we observe a statistically significant higher SNR. We do not observe statistically significant differences on SDNR for both $200\mu m$ and $300\mu m$ microcalcifications, when using rigid or flex paddle. Therefore, despite a breast thickness varying linearly from chest wall to nipple when the flex compression paddle is used, the image quality is preserved or improved compared to the image quality obtained with the rigid compression paddle.

In a clinical study, Broeders M.J. et al. [15] have also compared the image quality and patient comfort between the standard rigid and flex paddles. According to the authors, the standard flex paddle performed slightly better image quality in the projected breast area, however it moved breast tissue from the image area at chest wall side. According to our compression simulation, for the small breast volume, no difference in tissues lateral displacement was observed. On the other hand, for the larger breast, using the flex paddle has indeed increased the tissues displacement toward the chest wall side , but not by more than 4 mm (Figure 5.11).

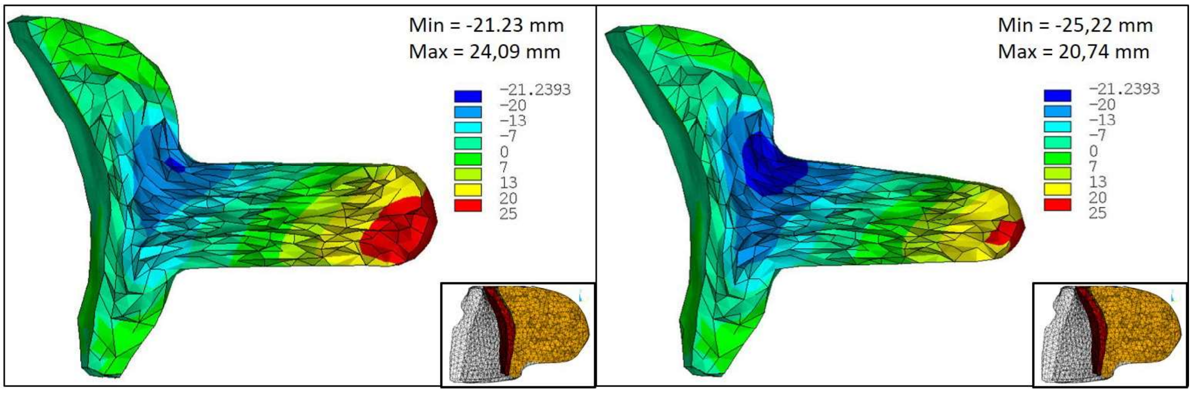

Figure 5.11: Node displacements on the direction parallel to the paddle (Oy axis).

To assess the patient comfort during compression, the resulting internal stress and strain distributions, as well as the contact pressure maps were derived. These data were collected at compressive forces of 22 N for the first volunteer (Figure 5.12) and 95 N for the second one (Figure 5.13).

Regarding the smallest breast volume (Figure 5.12), there is no significant difference between FPM and RPM in pressure distribution over the skin surface or in internal stress/strain intensity distributions. For both compression paddles, high pressure at the skin surface is concentrated in the juxtathoracic region with a maximum pressure of 77.7 kPa. In addition, the FE simulations confirm that in small breasts the paddle tilt is too small to impact the tissues compression in the middle part of the breast. FPM applied on larger breast volumes (Figure 5.13) results in significantly lower intensities of pressure at the skin surface in contact with the compression paddle, with a maximal pressure of 37 kPa, compared to 56 kPa when using RPM. No significant difference in the measured maximal intensities of strain and stress was observed, however strain and stress distribution patterns are different. When the breast is compressed with a rigid paddle, maximal strain and stress are concentrated in the retromammary space and decrease considerably toward the nipple. When a flex paddle is used, stress and strain are more uniformly distributed over the breast volume with the highest values in the middle third of the breast.

The area pressure distribution patterns have already been demonstrated in the work by Dustler M. et al. [38]. The authors have studied the pressure distribution patterns of 103 women undergoing breast compression with a rigid paddle at different compression levels. Four groups were differentiated: a) skin pressure widespread over the breast (29%); b) skin pressure concentrated on the central part of the breast (8%); c) skin pressure concentrated on the juxtathoracic region (16%); d) skin pressure concentrated along a narrow zone at the juxtathoracic region (26%). The pressure distribution patterns observed for our first and second volunteers correspond to the group d) and a) respectively.

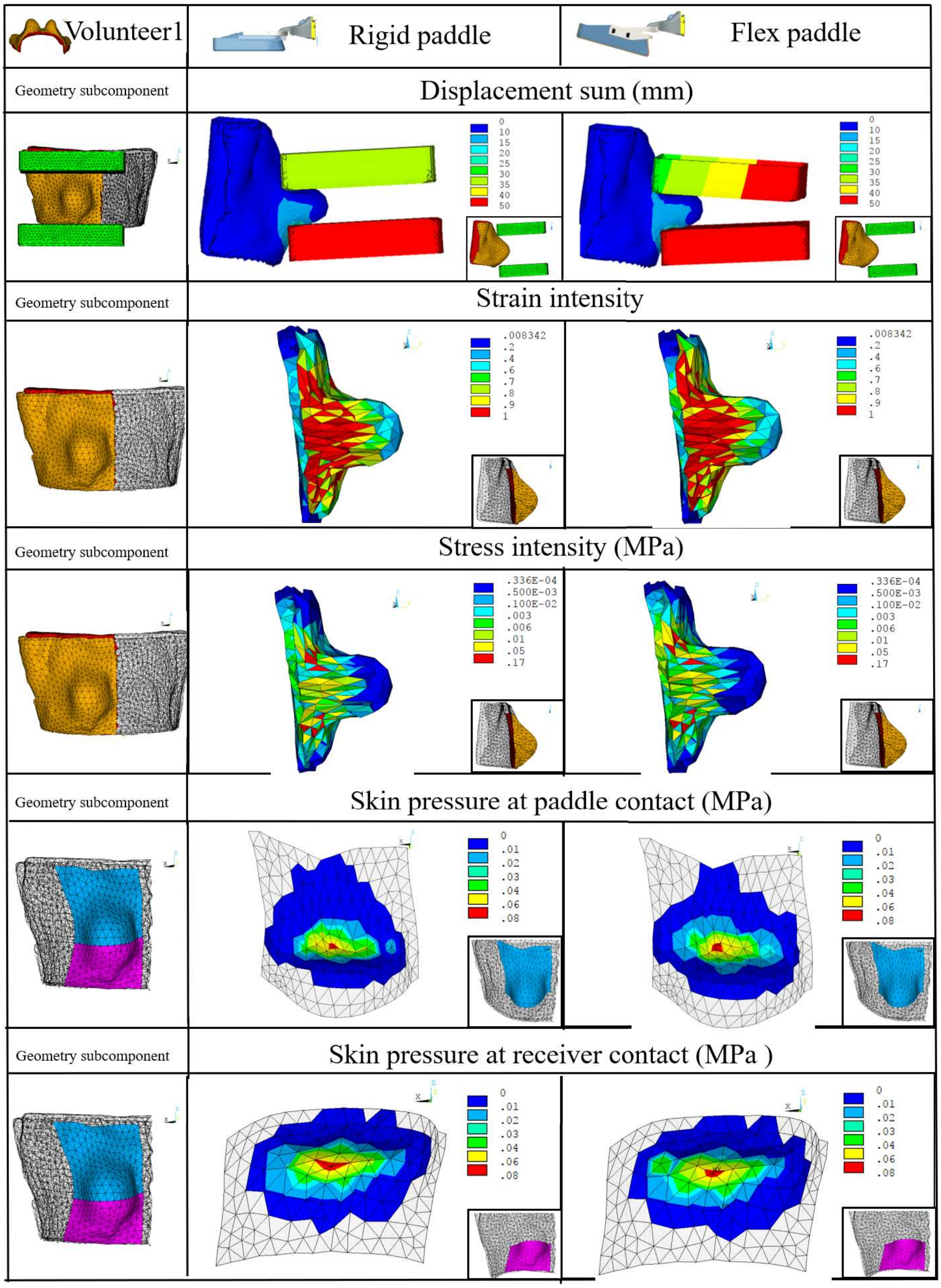

Figure 5.12: Stress, strain and contact pressure distribution for the first volunteer

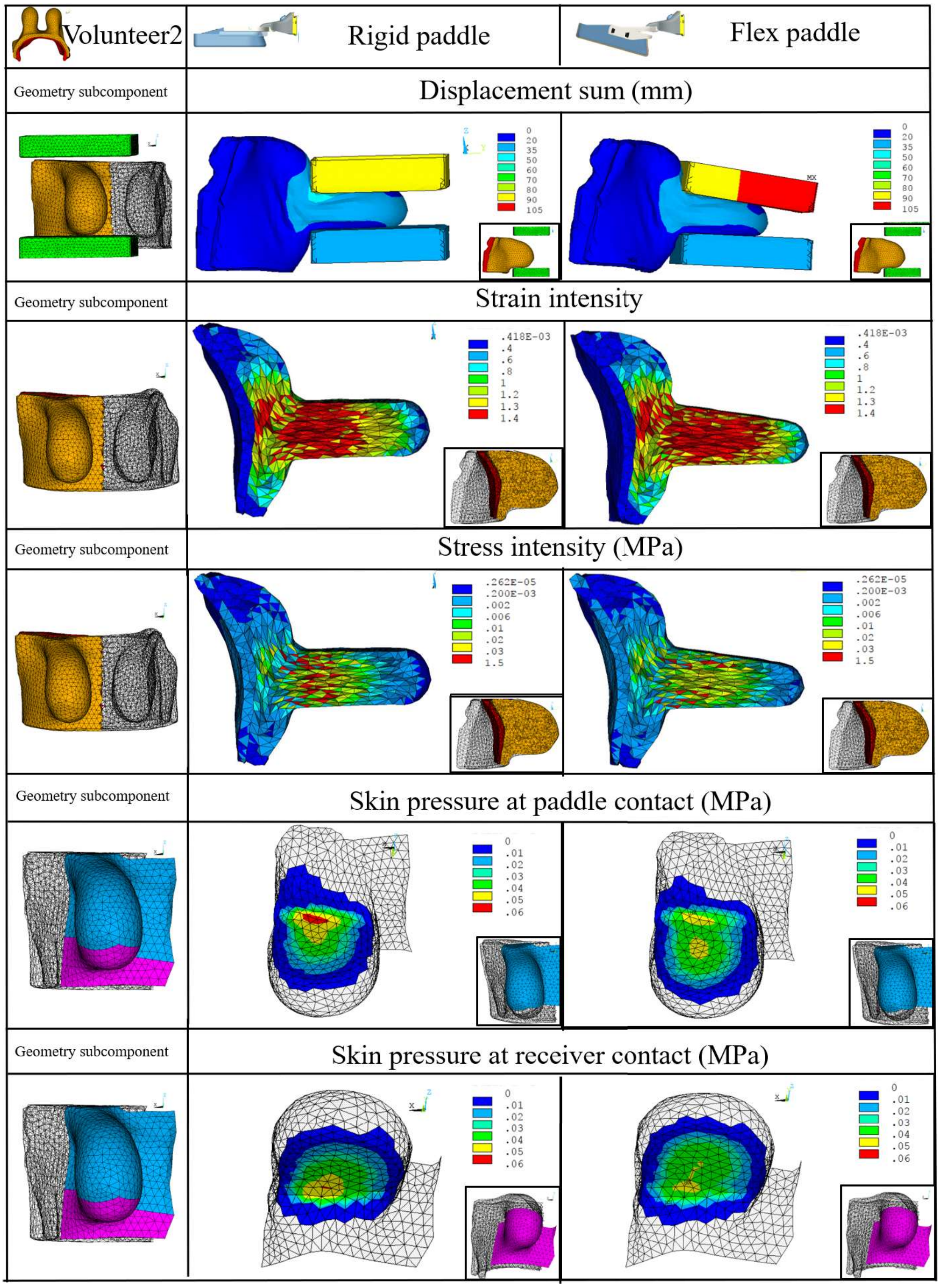

Figure 5.13: Stress, strain and contact pressure distribution for the second volunteer

5.4.2 Paddle positioning impact on compression mechanics

A second study was performed in order to assess the paddle positioning impact on the compression force. The simulations were performed only on the right breast of the second volunteer. Indeed, the geometry of the first volunteer is too small and does not meet the necessary morphological criteria required by this study.

Using the rigid paddle model to perform compressions with different paddle position in respect to the thoracic cage (thoracic cage to paddle distance TPD, Figure 5.15) has generated large convergence problems. For example, when the paddle was positioned closer to the chest wall, the finite elements were distorted because of high contact pressure at the juxtathoracic are. Therefore, for further investigations, the elastic paddle model was used. This model is closer to the mechanical properties of the standard rigid paddle from a mammography unit. In addition, material elasticity allows a slight paddle bending which seems to reduce elements' distortions.

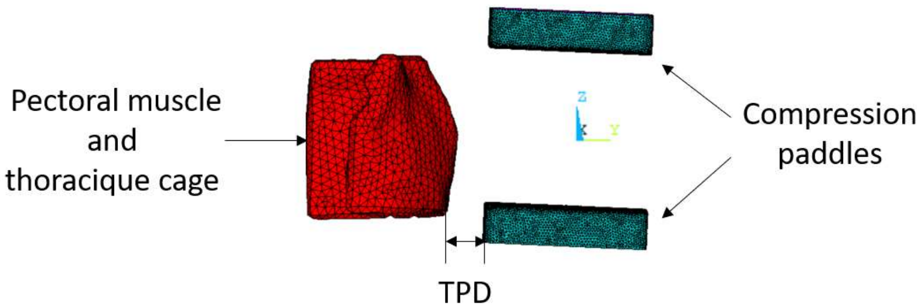

Figure 5.14: Thoracic cage to paddle distance (TPD).

The breast was compressed until a minimal thickness of $50mm$ was reached. Then, the compression force as well as surface pressure at the contact with the compression paddle were compared. The compression force was computed as the product between the mean surface pressure and the contact area $\langle P_{contact} \rangle * A_{contact}$.

Figure 5.15 shows the strain/stress as well as the pressure distributions over the contact area for three distinct distances TPD between the paddle and the thoracic cage. The compression force varies considerably within paddle positions. A compression force of 59 N, 94 N and 158 N was obtained when the paddle was positioned at a distance from the chest wall of 48 mm, 40 mm and 33 mm respectively. Positioning the paddle with 15 mm closer to the chest wall tripled the force intensity.

Due to the paddle elasticity, the breast thickness slightly varies, with a maximal deflection equal to 3.5 mm (Figure 5.15 first line). A very small difference between the maximal paddle deflection (~ 1 mm) was observed within the previous three compressions. Thus, image quality or AGD were not significantly impacted by the breast thickness variation. However, the wider the space between the chest wall and the compression paddle, the fewer breast tissues in the projected mammography image. In a standard framework, the

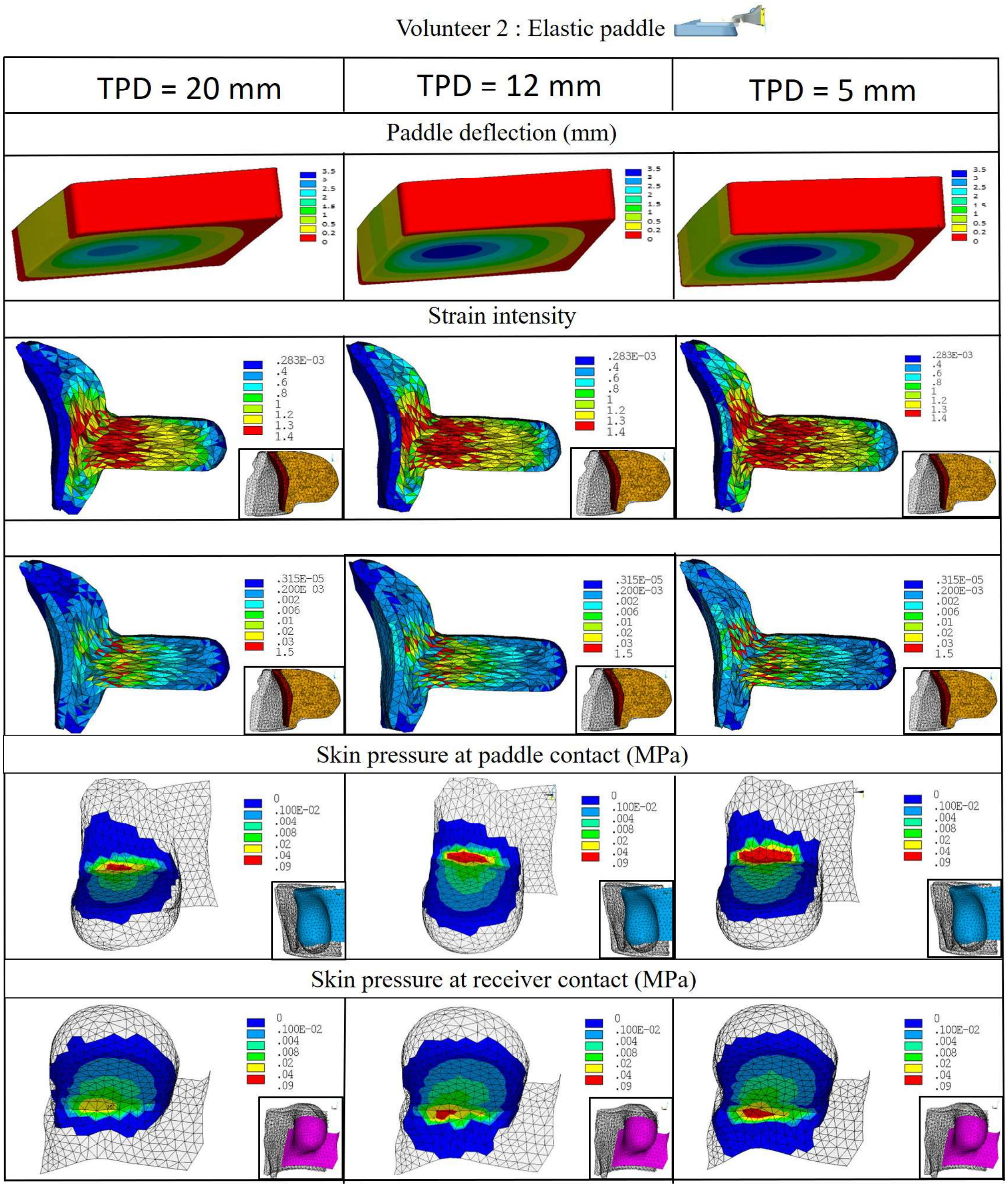

Figure 5.15: Stress, strain and contact pressure distribution for a variable thoracic cage to paddle distance (TPD).

technologist will include as much breast tissues as possible in order to reduce the risk of missing a suspicious lesion.

When looking at the strain distribution, one can see that, when the compression paddle is positioned closer to the chest wall, the juxtathoracic soft tissue undergoes higher deformation resulting also in a higher stress intensity. Concerning the skin surface pressure distribution, the highest intensities ($\sim 90\ kPa$) are always concentrated in the juxtathoracic area. However, for a thorax to paddle distance equal to 33 mm, the area corresponding to the high pressure is considerably larger. This means that a significant part of the total force was used to compress the tissues in the juxtathoracic area only, which may increase the patient discomfort.

5.5 Discussion and conclusion

In this chapter, the breast compression was simulated using three paddles models, the rigid, flex and elastic models. In order to comply with the compression mechanics as described in literature, an update of the tissues constitutive models was needed. Appling the Gent form of strain-energy potential, instead of the Neo-Hookean form, allowed to obtain compression force magnitudes comparable with the real subject data. However, when the same law is used to perform the multi-loading gravity simulations, the breast deformations in supine and prone configurations are over-constrained. We found that, with a larger value of J_m parameter, the Gent model may improve the breast geometry estimates obtained with a Neo-Hookean model. In conclusion, the estimated value of J_m does not characterize the subject-specific mechanical properties and gives only an estimation of a standard behaviour. Our second study shows that, to obtain a proper estimation of parameter J_m, more information like the paddle position with respect to the breast volume is needed.

The patient comfort (measured as strain and stress) as well as the image quality (measured as SNR, SDNR) and AGD were compared for breast compression with rigid and flex paddles. The results from the two volunteers were analysed. The compression simulations indicate that, for the smallest breast, there is no significant difference for the patient perceived pain when using the rigid or the flex paddles. We did not observe any statistically significant difference in SNR or SDNR for microcalcification of any size. Therefore, our results suggest that using a flex paddle should not significantly impact image quality and delivered dose in small breasts and should not reduce significantly the perceived pain. For the largest breast, our simulations indicate that using a flex paddle may reduce the maximal pressure intensity on the skin surface by about 30% compared to the rigid paddle. The tissues deformation is more uniformly distributed inside the breast volume, and the highest deformation occurs in the middle breast region corresponding to the supposed location of dense tissues. Moreover, our simulations have shown that the flex paddle has no significant impact on the average glandular dose and improves image quality compared to the rigid paddle. However, breast compression with a flex paddle is suspected to facilitate the displacement of the fibroglandular tissues into the retromammary area. As the breast thickness increases linearly from the nipple to the chest wall, the retromammary area is characterized by a low image quality.

The impact of paddle positioning on patient comfort and image quality was also addressed. Three paddle positions with respect to the chest wall were studied using the elastic compression paddle. Even if a variable breast thickness is obtained due to the paddles deflection, the variations are too small ($\sim 1mm$) to impact the AGD or the resulting image quality in terms of the SNR or SDNR. However, by excluding the retromammary tissues from the imaged area, information on small posterior cancerous legions may be lost. In terms of patient comfort, the simulations have shown that the high pressure are always localized in the juxtathoracic areas. When the paddle is too close to the chest wall, the compression force is mostly dissipated on this narrow area resulting in very high pressures compared to the skin pressure over the breast ($90kPa$ vs $10kPa$).