OPTIMIZING A BIOPSY NEEDLE USING A SIMULATION MODEL

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ABSTRACT

The method of biopsying biological tissue is an established procedure of minimally invasive medicine to extract samples for the determination of the presence or extent of a disease. Therefore punch biopsy is the most frequently applied method in case of prostate or breast cancer. The biopsy system is monitored during the penetration process into tissue via sonography. These observations of the procedure showed a considerable deflection of the needle tip. It is caused by unbalanced forces acting on the tip and by the low bending stiffness of the system itself.
Government financed experimental studies using realistic phantom tissue have been conducted to quantify the needle deflection and to develop a mathematical approach to simulate this effect. This simulation has used a combination of a deformable model of the biopsy system in combination with a parameterized tissue model in multibody simulation software Recurdyn. It is now possible to anticipate the needle deflection, to get to know about the acting forces and to optimize the geometry of the needle tip.

1. INTRODUCTION

Biopsying within the context of minimally invasive medicine allows to extract samples for the determination of the presence or extent of a disease. Punch biopsy is the most commonly chosen procedure to verify suspect tissue. Observations detected considerable deflections of the needle tip. This worsens the accuracy of the puncture and the quality of the samples.
Publicly financed experimental studies using realistic phantom tissue have been conducted to quantify the needle deflection and to develop a mathematical approach to simulate this effect.
The result of the studies is a validated simulation model including a deformable model of the biopsy system and also a parameterized tissue model. It is now possible to anticipate the needle deflection, to get to know about the acting forces and to optimize the geometry of the needle tip.

2. PUNCH BIOPSY

The procedure of a punch biopsy is performed in five steps, as shown in Fig. 1. In the first step, the punch biopsy system, composed of an inner needle with a notch sampling the tissue and an outer cannula to cut the tissue (Fig. 1-1), is positioned near the area of interest. Commonly, the position is monitored via sonography. Then the inner needle gets shot into the area of interest (Fig. 1-2) and the tissue slides into the notch (Fig. 1-3, 1-4). Next, the outer cannula moves forward with high speed and cuts the tissue, providing a sample of high quality (Fig. 1-5). In the final step, the whole system is removed from the body (Fig. 1-6).

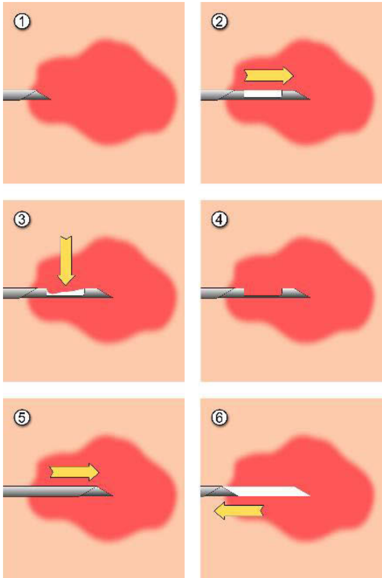

Figure 1: Basic phases of the biopsy [1]

3. PHANTOM TISSUE

Although the procedure is monitored, it is not guaranteed to get the sample from the area of interest. This is caused by the deflection of the needle tip. Because of strict ethical standards applying for the usage of human or animal tissue, there has to be an alternative tissue as real as possible for further examinations. This “realistic” phantom tissue is made of agarose powder mixed up with different proportion of water. The results are transparent, non-toxic gel blocks at various levels of stiffness, produced in a standardized way.
Currently, only homogeneous blocks are used, but in the future there will also be embedded structures to be even more realistic to biological tissue.

4. STUDIES OF THE NEEDLE DEFLECTION

One of the most common needle tip geometries is the so called bevel tip (Fig. 2). It has a polished cut surface with a specified angle.

Figure 2: Needle geometry

Observations of the needle interaction during the whole process of a punch biopsy by use of a high speed camera provide the possibility to quantify the deflection of the needle tip. The snapshot (Fig. 3) shows a considerable deflection of the needle tip of about 8 mm.

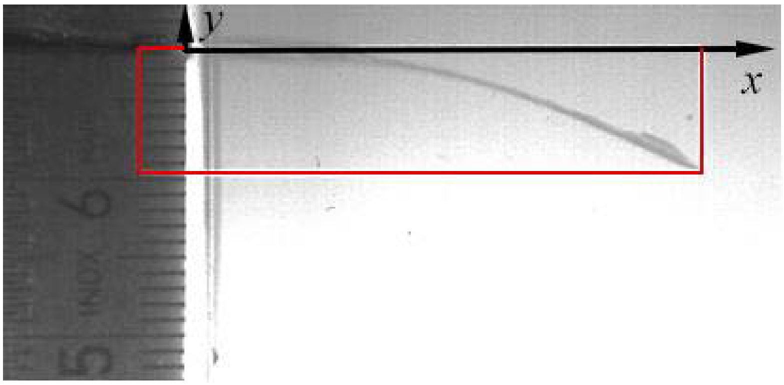

Figure 3: Deflection of the needle with bevel tip

During the following shot of the cannula, caused by its higher bending stiffness, it cannot follow the deflected inner needle. Therefore the inner needle is bended back by restoring forces and creates additional unnecessary traumas. Another effect is a reduced quality of the samples. These problems show for every commonly used punch biopsy needle system. As expected the higher the stiffness of the phantom tissue the more the needle is deflected. Whereas the diameter of the needle systems (usually between 0.9mm and 2.8mm) has no significant influence on the deflection. To reduce deflection, a new needle tip, trocar tip, has been developed. Thanks to this new geometry (Fig. 4), the needle tip deflection is halved to only 4mm (Fig. 5).
For further optimizations of needle tip geometries, still to reduce deflection and unnecessary traumas, a more time and cost efficient way than the experimental development has to be tried. The usage of the multibody simulation software Recudyn seems to be the best practicable way in reducing the number of experiments and developments costs but also in accelerating the procedure of development.

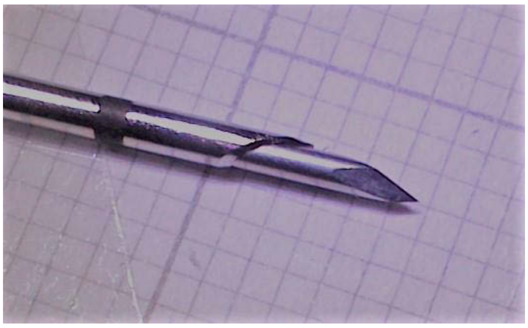

Figure 4: Trocar tip

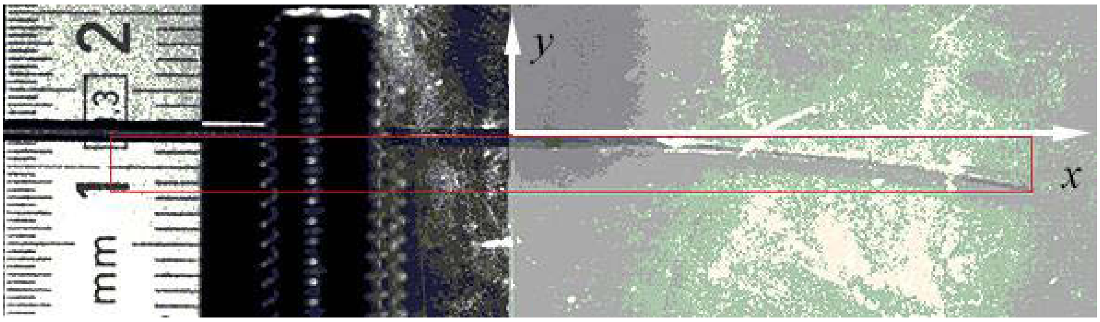

Figure 5: Deflection of the needle with trocar tip

5. SIMULATION

The analysis of the data given by high-speed records allows an adaption of the simulation model. The following data have been assessed:

- time-dependent curve ks of the needle tip (xs = xs(t), ys = ys(t))
- angel of deflection of the whole system

On this base, a mathematical physical approach has been developed to simulate the insertion process in Recurdyn, with special regard to the model of the tissue.

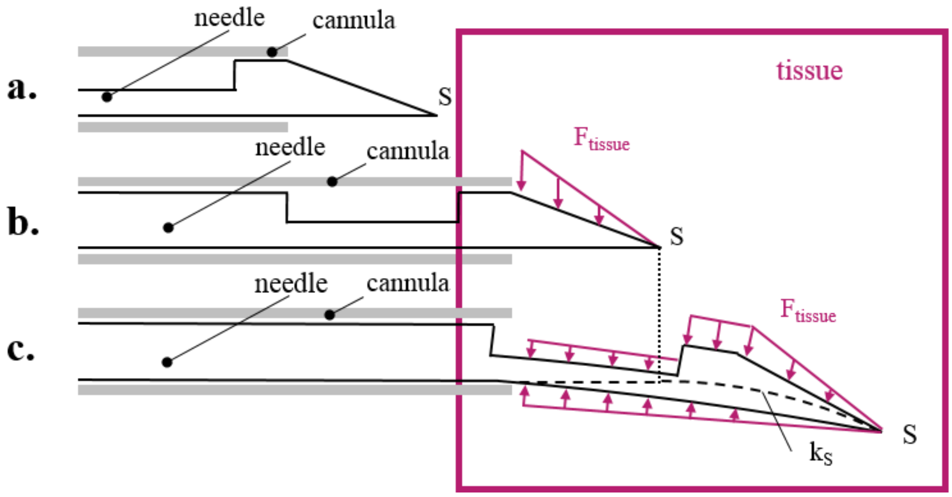

Figure 6: Phases of needle system insertion

The following steps were considered (Fig. 6):
In the beginning, there is no interaction between needle system and tissue (step a.). While flowing into tissue the ideal movement of the needle system is, caused by its high stiffness, straight on (step b.). Therefore the time-dependent curve k_s of the needle tip should be linear. The tissue above the needle system is now compressed and applies a force to the needle that, for a two dimensional approach, can be assumed as a linearly increasing line load. This tissue compression mostly depends on the geometry of the needle tip. During the shot of the inner needle into the tissue (step c.), the asymmetrical shape of the needle tip, the pliability of the inner needle and the only one-sided acted normal forces cause a deformation of the inner needle and hereby a compression of tissue beneath the needle system.
Based on this knowledge, several node pairs were defined which are connected to the untainted tissue by spring damper elements (Fig. 7). Without needle connection these node pairs are force-free and tense up in dependence on needle tip geometry while being spread. Before first contact

with the needle, the node pairs are perpendicular to the tip middle axis A, guaranteeing a tangential running-in of the tip bottom to the node pair. The defined contact between the geometry of the inner needle and the node includes normal as well as tangential forces whereas tangential forces have to be considered as friction forces. There is also a distinction between forces acting from above ($F_{o,n}$ and $F_{o,t}$) and from below ($F_{u,n}$ and $F_{u,t}$).

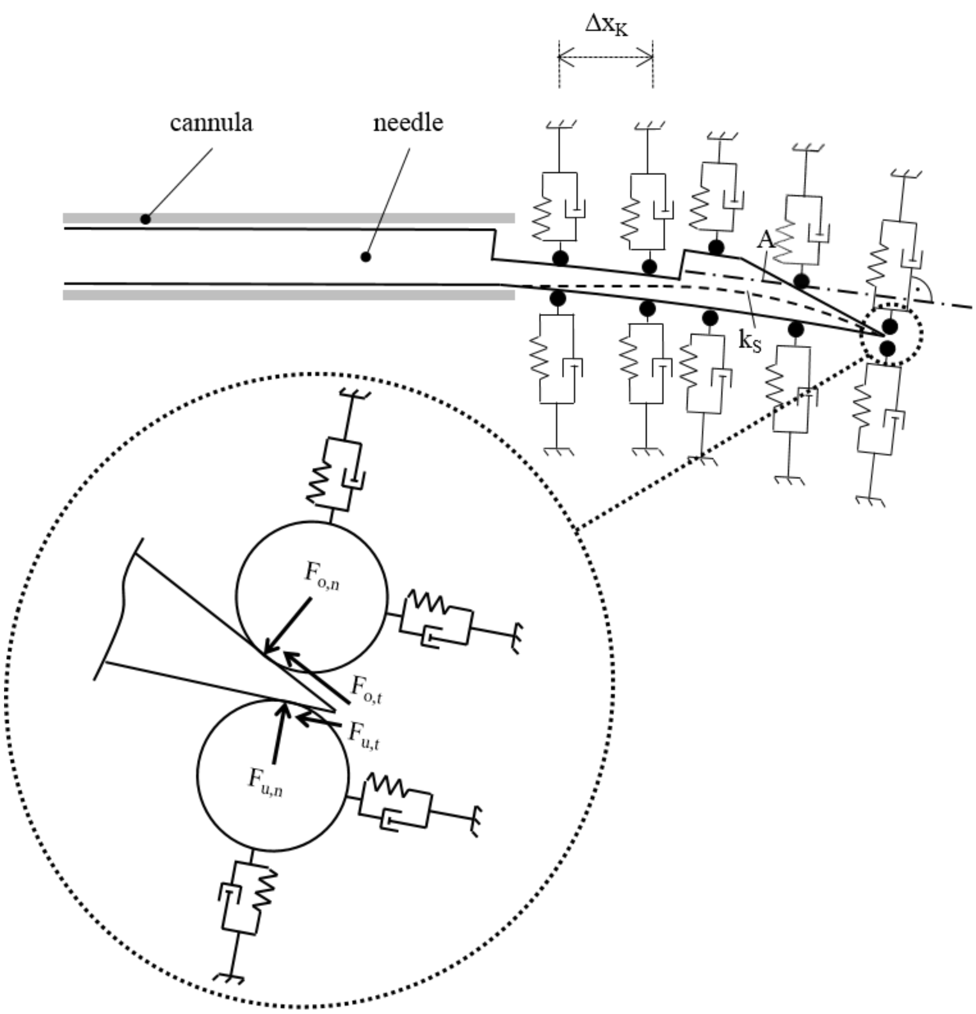

Figure 7: Schema of the simulation model

To model the real three-dimensional needle insertion into tissue with a two-dimensional approach, some additional influences to the penetration process have to be considered. The most relevant of these parameters are the contact forces (F_o, F_u) caused by tissue pressure following from the displacement of tissue. The third dimension is eliminated by a weighting factor that is established by projecting the standardized contact area on the xz-plane for each node pair.

This is shown in Fig. 8 for both bevel tip and trocar tip and node pairs i to n. Contact areas depend on needle geometry, distance Δx_K between nearby nodes and their current positions x_i, x_j, x_k, x_n on the needle.

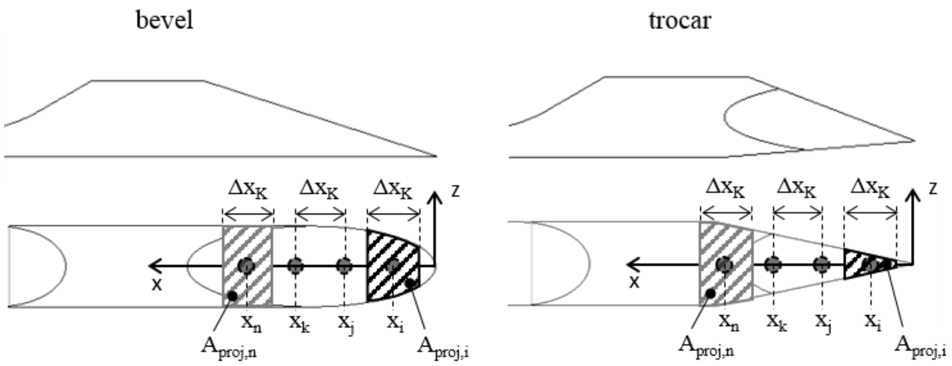

Figure 8: Needle with projected contact surface

A geometrical factor is defined to standardize all resulting forces depending on their relative position to the needle tip and node pair and on the needle geometry. This factor is needed to implement the effect of a changing contact area into the simulation model. The following figure (Fig. 9) represents the mathematical function of the projected and discretized contact area in a standardized way.

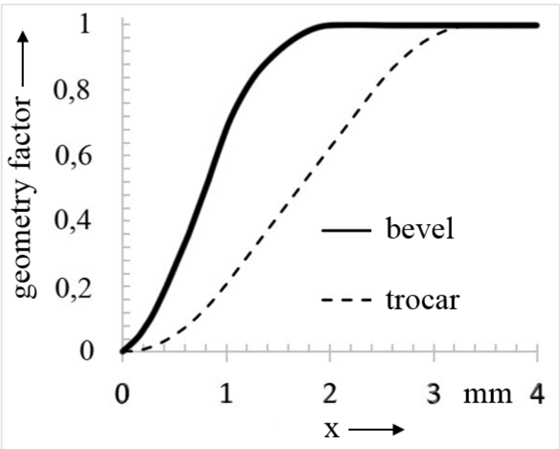

Figure 9: Geometry factor

Because of the manufacturing process, the mechanical properties of the needle have changed in comparison to the elemental material properties. Therefore it was necessary to perform some tensile tests. Furthermore, measurements to identify needle deflection by given forces were done to verify the simulation results. As shown in Fig. 10, both yield strength $R_{p0,2}$ and tensile strength R_m clearly depend on needle diameter.

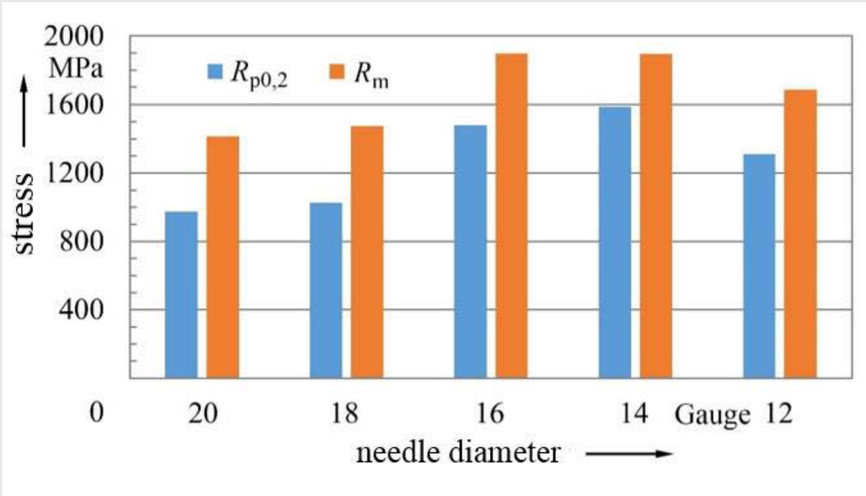

Figure 10: Results of the tensil test

Two different model strategies for the flexible needle in MBD-Software have been investigated: Modelling by assuming the needle as a meshed body and by partitioning the needle in discretized, connected beam elements (lumped mass model). The second method showed up to be the best strategy in terms of accuracy and CPU utilization and was chosen for further simulations. In Fig. 11 two time steps of the simulation process are shown.

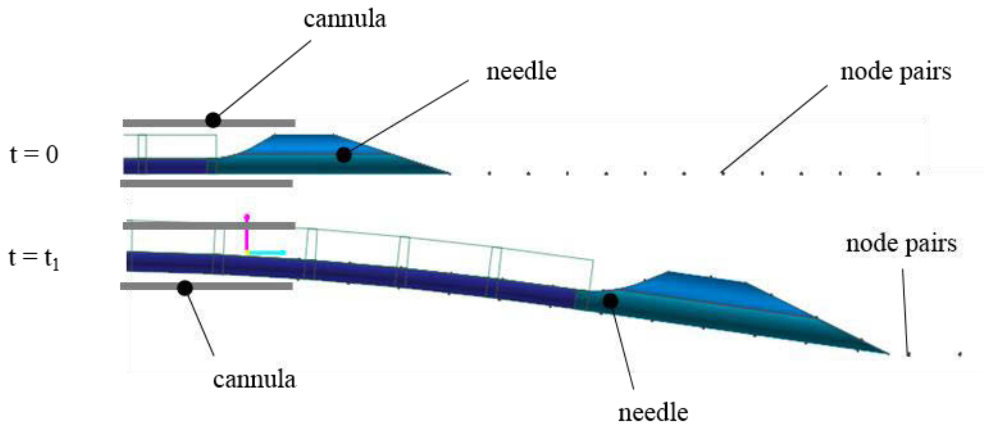

Figure 11: Simulation model

Parameterization of the simulation model and validation of its results was performed by testing different tip geometries using the results of the analysis of the high speed records. To include tissue reactions, a degressive force displacement curve was developed as demonstrated in Fig. 12.

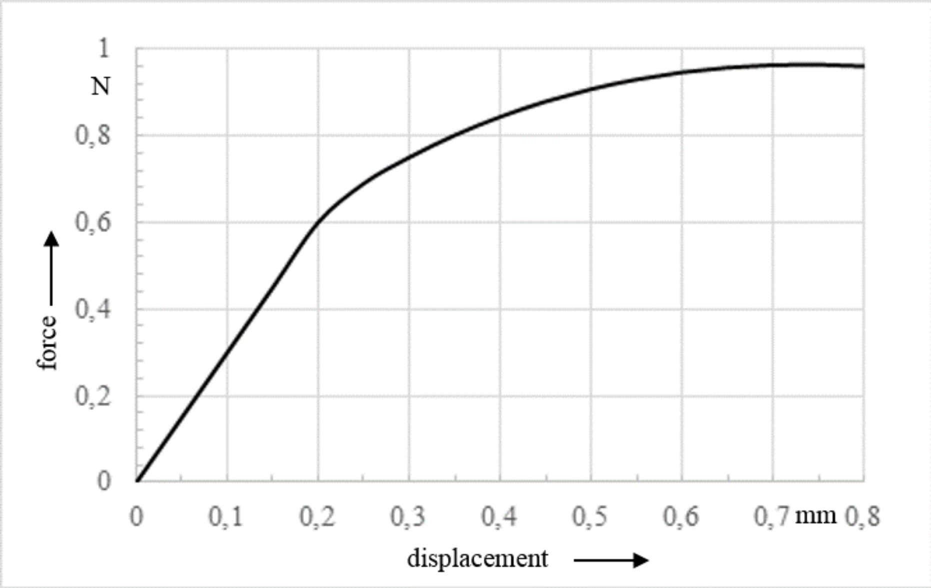

Figure 12: Forces-displacement-curve of a node

As shown in Fig. 13, simulation results and data out of the analysis of the high speed records for the two needle tip geometries (bevel and trocar tip) and a phantom tissue with a middle stiffness match widely. A maximal deviation of only $\Delta y = 0.3$ mm qualifies the model sufficiently for the development of a new and optimized needle tip geometry.

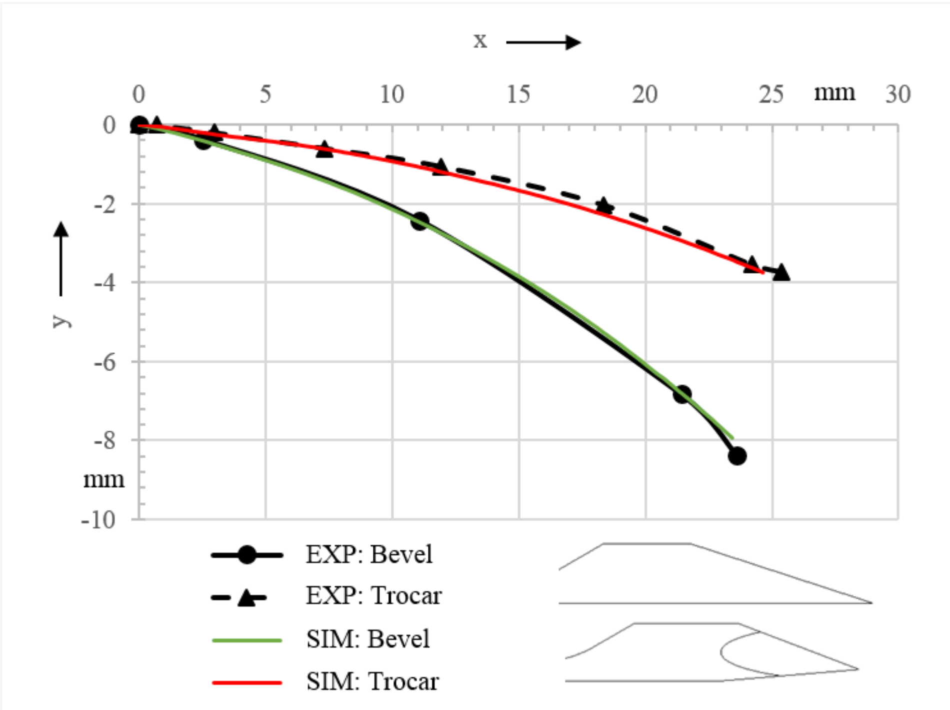

Figure 13: Results of the experimental studies and simulation

6. CONCLUSION

By use of realistic phantom tissue, it is possible to analyze the effects occurring during the biopsy process. Based on these results, a simulation model has been developed that reproduces the observed effects of the experimental studies with high approximation.
The model allows further examinations with the aim of a needle system without deflection.

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