4 The Physics of Follicular Unit Extraction

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BACKGROUND

Follicular unit extraction (FUE) is a relatively new method for harvesting individual follicular units (FUs) from the donor region of the scalp. This technique is based on isolating and harvesting individual FUs from the donor area in order to use as grafts.[2,3] The method may be performed by a manual punch, a motorized punch device, or more recently by a robotic system.[4,5,6]

Follicular unit extraction has been gaining in popularity because it is considered a minimally invasive technique. However, the skin and scalp trauma to the donor area and high transection rates compared to single-strip harvesting remain the main concerns for an FUE hair surgeon.

The study of medical physics involves the application of mathematics and general physics concepts, theories, and methods to healthcare. As a physician, I have been working in the field of FUE hair transplantation for over 12 years. My academic background also includes doctoral studies as a medical physicist. It is my earnest desire to explain how the principles of medical physics and methods of mathematical modeling can be applied to reduce the follicular transection rates as well as donor scalp injury caused by FUE donor harvesting.

In cooperation with my colleagues at the University of Patras (Patras, Greece), a system called the Advanced Image Processing System was developed that uses physics and mathematical parameters. This software is commercially known as Follysis, and I primarily use it in my hair-restoration practice and academic environment. Follysis is a device that automatically recognizes FUs on microphotographs and calculates important characteristics of the scalp like hair/graft density. Moreover, I personally believe this system allows for the best and most effective use of the FUE technique by minimizing skin injury and improving the quality of the extracted grafts.

Editors' Note: Dr Zontos' chapter represents a remarkable contribution to the field of FUE in establishing parameters of safety and understanding the requisite dynamics of FUE physics. However, some of the detailed mathematical formula can be difficult for the reader to follow easily. Nevertheless, we believe strongly this material adds to the academic discussion and deserves publishing within this comprehensive volume dedicated to FUE.

INTRODUCTION TO THE FUNDAMENTAL PRINCIPLES OF FUE

In my opinion, one of the major problems of the FUE donor-harvesting technique is the transection of the FUs. This is known as the transection rate and is equal to the percentage of FUs that are transected during the extraction. Any increase in transection rate consequently causes the following:

1. Greater injury to the donor area because more harvesting attempts are required
2. Increased donor-harvesting time to obtain grafts
3. Potential long-term irritation and discomfort to the patient, as the remaining part of the transected FU continues its cellular division under the skin

The transection rate n is defined as follows:

$$n=\left[1-\frac{\text{number of extracted FUs}}{\text{number of holes}}\right].100\%=\left[1-\frac{\text{number of grafts obtained}}{\text{number of punch attempts}}\right].100\% \quad (4.1)$$

This equation reflects the yield of the harvesting process. In short, the higher the n, the lower the yield.

In my model, I have found that if $n \leq 5\%$, the donor-harvesting process will be easy. If $5\% < n \leq 10\%$, the harvesting process is acceptable. If $10\% < n \leq 20\%$, the harvesting process is considered difficult and may be continued either if the session is short or if the FUs are directly removed from the donor region immediately and implanted in the recipient sites. If $n > 20\%$, I recommend pausing for reassessment or termination of the procedure.

But I believe the transection rate alone is insufficient to assess the quality of the extraction. For that purpose, a new mathematical factor is introduced that I call ratio $\lambda = \frac{h}{g}$, where h = number of hairs, g = number of obtained grafts.

The factor λ expresses the average number of hairs per extracted FU. To emphasize the importance of λ, let us look at an extraordinary situation and case in an FUE procedure. Suppose the scalp donor area is filled with multiple FUs and the $n \leq 10\%$. This does not mean that the extraction will be successful, as the majority of the FUs could be singles and not intact. Therefore, n fails to describe this particular clinical situation. The calculation of λ during the procedure will enable the surgeon inclined to medical physics to evaluate quantitatively the success of the donor-harvesting process.

Based on my experience, I calculate the value of λ at the beginning of the procedure by collecting 100–200 grafts and counting the total number of hairs. My assistants are in charge of separating the FUs into different Petri dishes of 1, 2, 3, 4 or more hairs, and they divide the total number of hairs by the total number of grafts to get the value of λ.

After performing over 3,000 FUE procedures, when evaluating whether the FUE donor harvesting is effective, I follow the following rules:

1. If $\lambda \geq 2.3$, the procedure is successful and the case continues.
2. If $\lambda \leq 1.8$, the procedure should be stopped. This decision is based on the high probability of harvesting inferior quality grafts, as the majority of grafts will not be intact (with body-hair being excluded).
3. If λ is between 1.8 and 2.3, the decision to continue the procedure is based on the calculation of a new mathematical factor, the partial ratio $\lambda_p = \dfrac{\lambda_e}{\lambda_d}$ (4.2), where λ_e is the ratio of the procedure, while λ_d is the ratio of the donor area.

In order to calculate λ_d and before starting the harvesting process, I take microphotographs from the most important sections of the donor area. Each picture frame is processed by Follysis to automatically count both the number of FUs and hairs. Then, the system divides the total number of hairs by the total number of grafts to find the value of λ_d (Fig. 4.1).

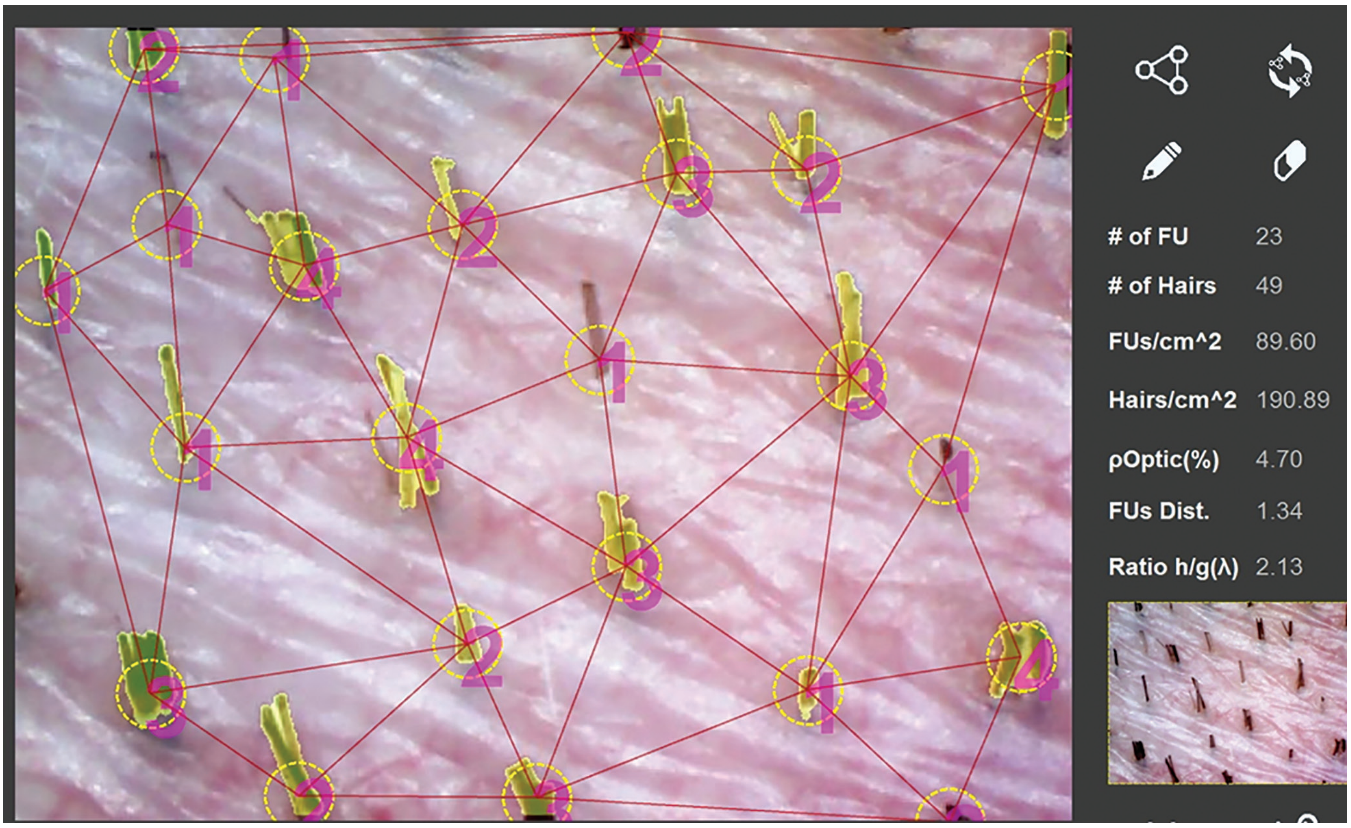


Figure 4.1

Automatic calculation of λ = 2.13 by Follysis

Having calculated λ_d and λ_e by using equation (4.2), we can find λ_{ρ}. Based on my experience

If $\lambda_{\rho} \geq 1$, the procedure should continue, but

If $\lambda_{\rho} < 1$, the procedure should be stopped.

In describing my medical physics model, it needs to be emphasized that λ_{ρ} is related to the partial transection rate, so the higher the partial transection rate, the lower the value of λ_{ρ}.

To clarify, partial transection is the condition in which the obtained grafts have one or more of their follicles transected. Therefore, the partial transection rate is the percentage of the obtained grafts that are not intact.

The calculation of n, λ, and λ_{ρ} is vital to evaluate the progress of an FUE procedure.

THE OUTGROWTH ANGLE MODEL[7]

Geometry, Medical Physics, and Exit Hair Angle

The injury to the donor area caused by the scoring during donor harvesting is a significant concern to patients and physicians. The resulting appearance of the donor region of the scalp when healing is complete can result in multiple, small white dots referred to as hypopigmentation. It may be noticeable if the patient's hair length is 1–2 mm (Fig. 4.2). It is less or unnoticeable if the hair length is >4–5 mm.

Figure 4.2

Numerous tiny scars or hypopigmentation seen in the donor area

The amount of donor injury depends on several factors such as the punch diameter, the number of extracted FUs per square centimeter, the transection rate,[5] the distance between the FUE entry sites, and the number of previous FUE procedures. In general, the more surgical procedures the patient has experienced, the higher the rate of donor injury.

Based on the following mathematical calculations, one of the most important factors is the exit angle of the emerging hair follicles. In order to address this problem, I always refer to my mathematical model that

1. Determines the relationship between the angle and the injury,
2. Uses a specific formula that calculates the exact percentage of skin trauma, and
3. Provides information on how the trauma can be reduced.

In order for an FU to be extracted intact from the donor area, the axis of the punch should be aligned with the exit angle of the hair on the skin surface. The hair exit angle of one follicle is not always the same as the other hair exit angles within the same scalp region. An even more complicated concept is the hair direction beneath the skin's surface may be at a different angle than the emerging exit angle of the hair follicle on the scalp. This makes FUE donor harvesting challenging.

The donor-harvesting experience can be explained in terms of simple geometry. Figure 4.3 represents the cylinder of the punch cutting the surface of the skin at a certain angle *z*, where *z* is the outgrowth angle of the hair follicles.

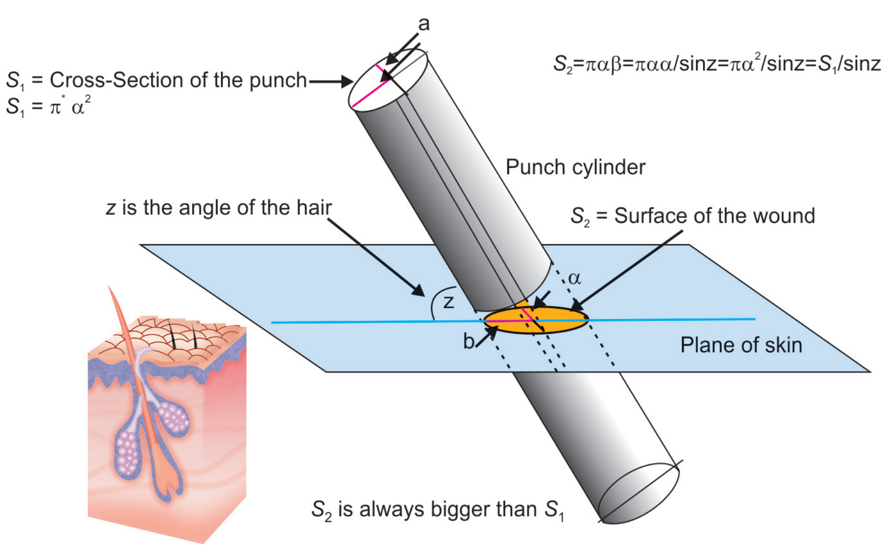


Figure 4.3

Illustration showing the surface area of the wound (S_2) diameter is larger than punch cross-section (S_1) when the exiting hair angle is not perpendicular
Photo Courtesy: Adapted with the permission of Dermatologic Surgery from Zontos G, Rose P, Nikiforidis G. A mathematical proof of how the outgrowth angle of hair follicles influences the injury to the donor area in FUE harvesting. *Dermatol Surg*. 2014;40(10):1147-50

It can be observed that while the punch cross-section (s_1) is circular, the shape of the wound (s_2) is elliptical. Based on this important observation, we can find from trigonometric theory that

$$s_2 = \frac{s_1}{\sin z}.$$

Presuming that α is the radius of the cylinder of the punch, we can safely make the assumption that one of the two semi-axes of the elliptically shaped wound is equal to α. The second one β is given by the formul $\beta = \frac{\alpha}{\sin z}$ (4.3)

So $S_1 = \pi\alpha^2$ (4.4), where $\pi = 3.14$,

while $S_2 = \pi.\alpha.\beta \overset{(4.3)}{=} \frac{\pi.\alpha.\alpha}{\sin z} = \frac{\pi.\alpha^2}{\sin z} \overset{(4.2)}{=} \frac{s_1}{\sin z}$ (4.5).

Since $\sin z$ ranges from 0 to 1 when $z \in [0, 90^o)$, s_2 is always bigger than s_1. This simple trigonometry equation explains why the punch causes a wound surface greater than its cross-section.[8] The greater the angle z is, the smaller the surface of the wound and vice versa.

The only case where $s_1 = s_2$ occurs when the outgrowth z is at 90°, allowing the axis of the punch to be placed perpendicularly to the skin surface (Fig. 4.4).

RESULTS

Given that the angle z is at $30° = \frac{1}{2}$. It is apparent that formula (4.5) implies $s_2 = 2s_1$. This means there is a 100% increase in the trauma caused by the punch.

The important concept for FUE surgeons to realize is the same-size punch causes different-sized diameter wounds in the scalp with varying and differing exiting hair angles (Fig. 4.5). The wounds produced by the same-sized punch at 90° and 30° again demonstrate this concept (Fig. 4.6). A punch wound that is 90° or

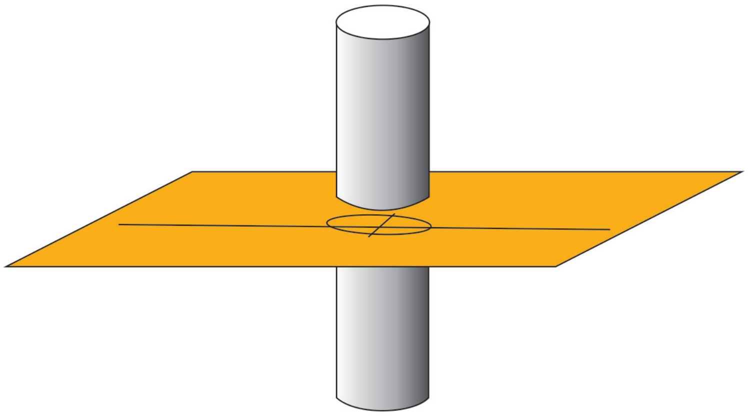


Figure 4.4

When the punch is placed at 90°, the wound surface is equal to the punch cross-section

Photo Courtesy: Adapted with the permission of Dermatologic Surgery from Zontos G, Rose P, Nikiforidis G. A mathematical proof of how the outgrowth angle of hair follicles influences the injury to the donor area in FUE harvesting. *Dermatol Surg*. 2014;40(10):1147-50

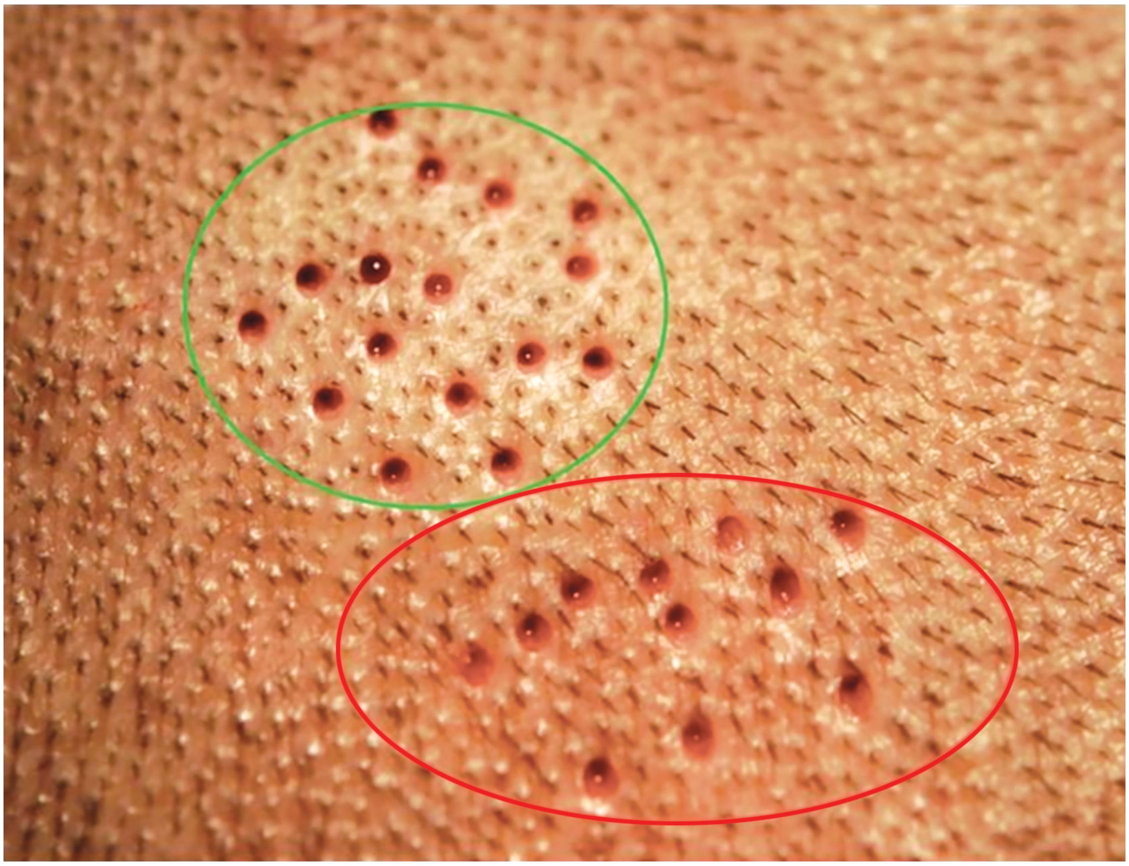


Figure 4.5

A 1.0-mm punch causes different-sized holes at different angles. The holes within the green circle were produced by placing the punch perpendicularly to the surface of the donor area, whereas the holes within the red circle were produced by placing the same punch at an acute angle

Photo Courtesy: Adapted with permission from Zontos G, Rose P, Nikiforidis G**.** A mathematical proof of how the outgrowth angle of hair follicles influences the injury to the donor area in FUE harvesting. *Dermatol Surg*. 2014;40(10):1147-50

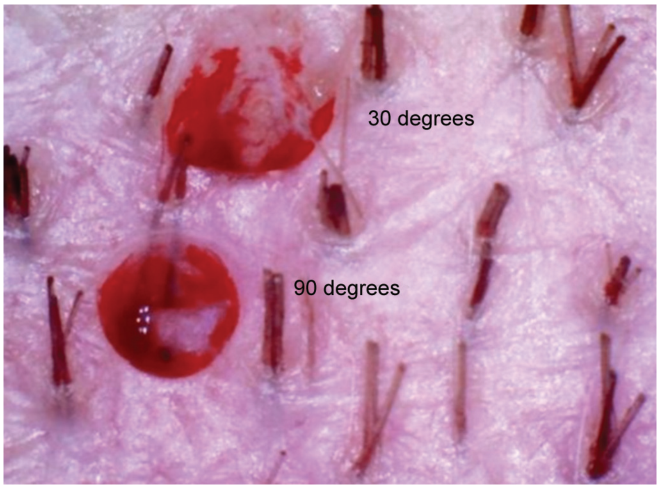
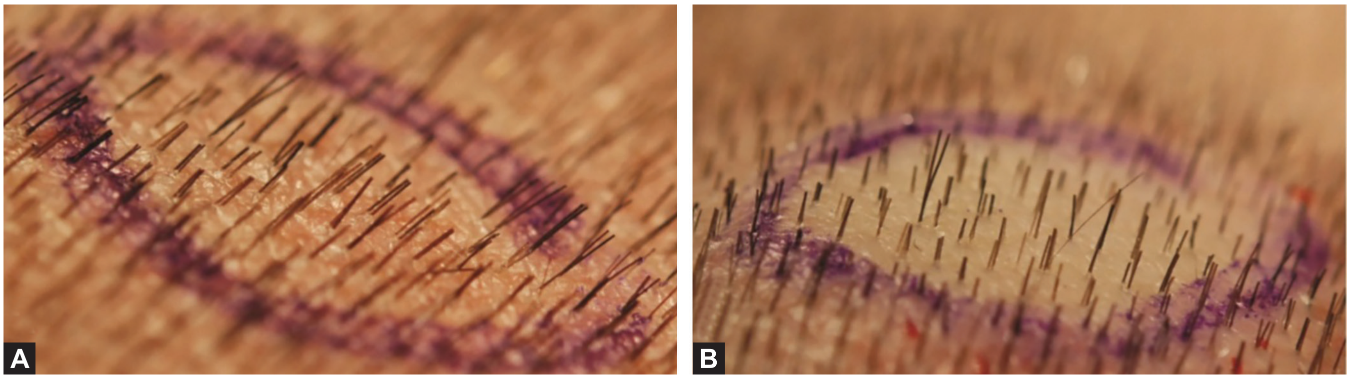


Figure 4.6

The microphotograph (ProScope HR2 digital micropicture, magnification 50×) illustrates the difference of each wound produced by the same-sized punch at 90° and 30°, respectively

Photo Courtesy: Adapted with the permission of Dermatologic Surgery from Zontos G, Rose P, Nikiforidis G. A mathematical proof of how the outgrowth angle of hair follicles influences the injury to the donor area in FUE harvesting. *Dermatol Surg*. 2014;40(10): 1147-50



Figures 4.7A and B

(A) Before injecting normal saline (B) After injecting normal saline intradermally. The hair follicles become more vertical, so the punch can be placed perpendicularly to the surface of the skin producing smaller sized holes

Photo Courtesy: Adapted with the permission of Dermatologic Surgery from Zontos G, Rose P, Nikiforidis G. A mathematical proof of how the outgrowth angle of hair follicles influences the injury to the donor area in FUE harvesting. Dermatol Surg. 2014;40(10): 1147-50

Video 1

perpendicular to the surface of the skin produces an equally round circle. A punch directed at a more acute angle creates an elliptical wound that is significantly larger in surface area than the perpendicular punch at 90° (Video 1).

TISSUE TURGOR AND REDUCING WOUND SIZE

To reduce the donor wound cross-section and surface area of the scalp wound, i.e., total area of hypopigmentation, I propose that normal saline be injected intradermally into the donor-harvesting area. By injecting normal saline intradermally, it causes the hair follicle to be more perpendicular to the skin's surface (Figs. 4.7A and B) and the value of sin z increases making the value of s_2 much smaller.

Based on the principles that the surface of the circle s_1 is given by the formula $s_1 = \pi\alpha^2$, where α is the radius of the punch, and the surface of the wound is given by the formula, $s_2 = \dfrac{s_1}{\sin z}$, we find that a punch size of 0.8 mm in diameter corresponds to a cross-sectional surface equal to 0.5024 mm^2 and causes a surface wound of 1.0048 mm^2 when the angle z is at 30°.

However, after injecting normal saline, a punch size 1.00 mm in diameter corresponds to a cross-sectional surface equal to 0.785 mm^2 and causes the same size of the wound when the angle z is at 90°.

The results are shown in Figure 4.8.

The gold columns represent the punch surface and the red ones, the corresponding injury. It is simple to calculate that a 1.00 mm punch has $\left(\dfrac{0.785-0.5024}{0.5024}\right)\% = 56.25\%$ larger cross-sectional surface than α 0.8 mm punch.

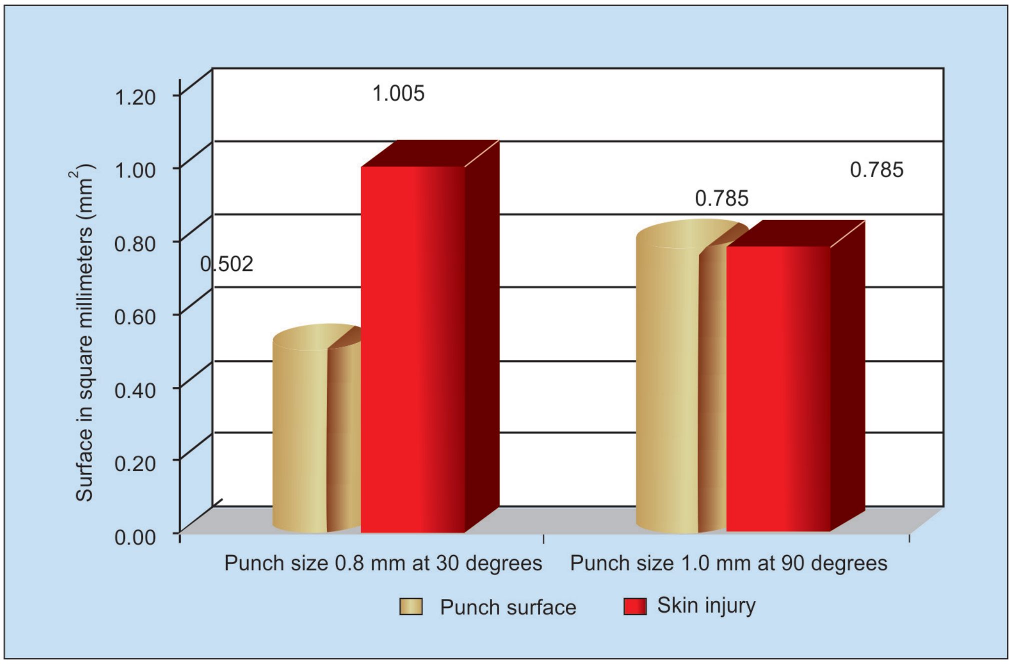


Figure 4.8

A 1-mm punch placed at 90° causes a smaller wound than a 0.8-mm punch placed at 30°. Even using a 56.25% larger cross-sectional surface punch, the skin injury decreases by 21.98%

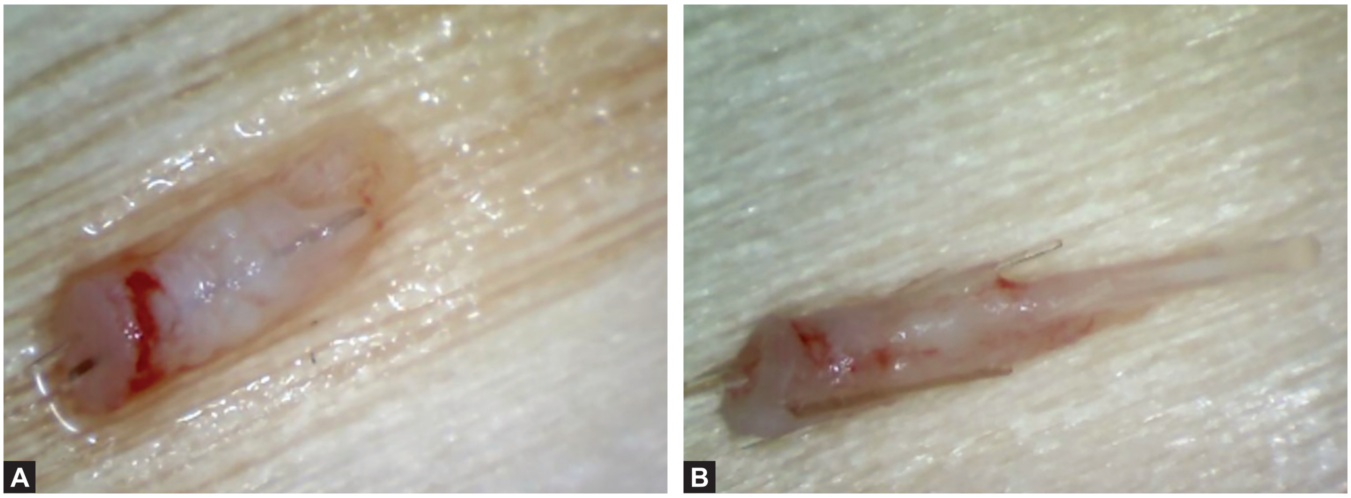
In addition, the percentage of the difference to the surface of the wound is $\left(\frac{1.0048-0.785}{1.0048}\right)\% = 21.98\%$

Even using a 56.25% larger cross-sectional surface punch, the skin injury decreases by 21.98% because injecting normal saline has modified the outgrowth angle.

THE HARVEST PROCESS MODEL

In FUE harvesting the main objective is to obtain intact grafts and to avoid transection of the FUs. Complete transection of an FU means the FU is amputated anywhere along on its horizontal axis (Fig. 4.9A). The International Society of Hair Restoration Surgery terminology committee officially defines transection to reflect *any microscopically visible breakage of a follicle anywhere along its entire length. A graft can be completely transected when all of its follicles are cut transversely. A partially transected graft occurs when one or more follicles are cut leaving one of more follicles intact* (Fig. 4.9B).

In a medical physics model, this means that the value of n remains <5%, while the value of λ_ρ is >1.



Figures 4.9A and B

(A) A totally transected follicular unit (B) A partially transected follicular unit

Figure 4.10

The photograph shows follicular units with 1, 2, 3, and 4 hairs

But how does this work in practice? To perform the technique, the long axis of the punch must be aligned with the exiting angle of the hair follicle. It is well known that the FUs may have 1, 2, 3, 4 or more hairs (Fig. 4.10).

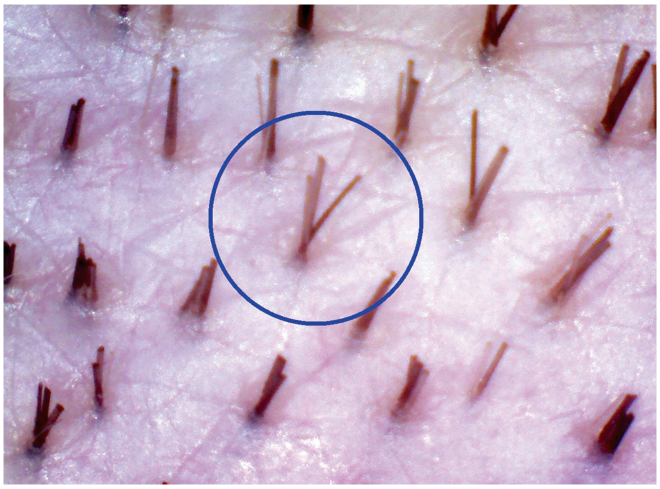


Figure 4.11

The microphotograph (ProScope HR2 digital microphotograph, magnification 50×) illustrates a deviation between the hair shafts

The hair shafts within an FU are not always parallel to each other because of follicular splaying (Fig. 4.11). If a smaller-sized punch is used and the physician operator does not limit the punch-penetration depth, follicular splaying potentially increases transection rates diminishing the quality of the extracted grafts.

A small punch causes less injury and a reduced wound size to the donor region of the scalp but can negatively affect the quality of the extraction decreasing ratio λ. On the other hand, a larger-sized circular punch may cause greater wound size, but the transection rate is lower and a more successful harvest is appreciated.

To overcome the problem of higher transection rates and lower graft quality, I use the following illustration (Fig. 4.12) where I apply the trigonometry of hair angulation when the cylinder of the punch is inserted into the skin at a certain angle z.

If d = the depth of the FU

r = the radius of the punch

ϑ = the maximum deviation of the hair shafts

Then I proved that the maximum lateral offset of the hair shaft is given by the formula (4.6) $x = \left(\frac{d}{\sin z} - r.\cot z\right).\tan\theta (4.6)$

Formula 4.6 shows all of the important factors that should be considered for a successful extraction.

In a rigid or theoretical mathematical formula, this means that when the exiting hair angle $z = 30°$, the depth $d = 4$ mm, and the radius of the punch $r = 0.5$ mm, the angle ϑ should be <3.8° in order for an FU to be extracted intact.

But if the deviation ϑ becomes >6° and the exiting hair angle z remains constant, a punch size of 1.54 mm has to be used in order to obtain an intact FU with a deeper penetration of the punch. In this theoretical model, the trauma to the skin also increases dramatically.

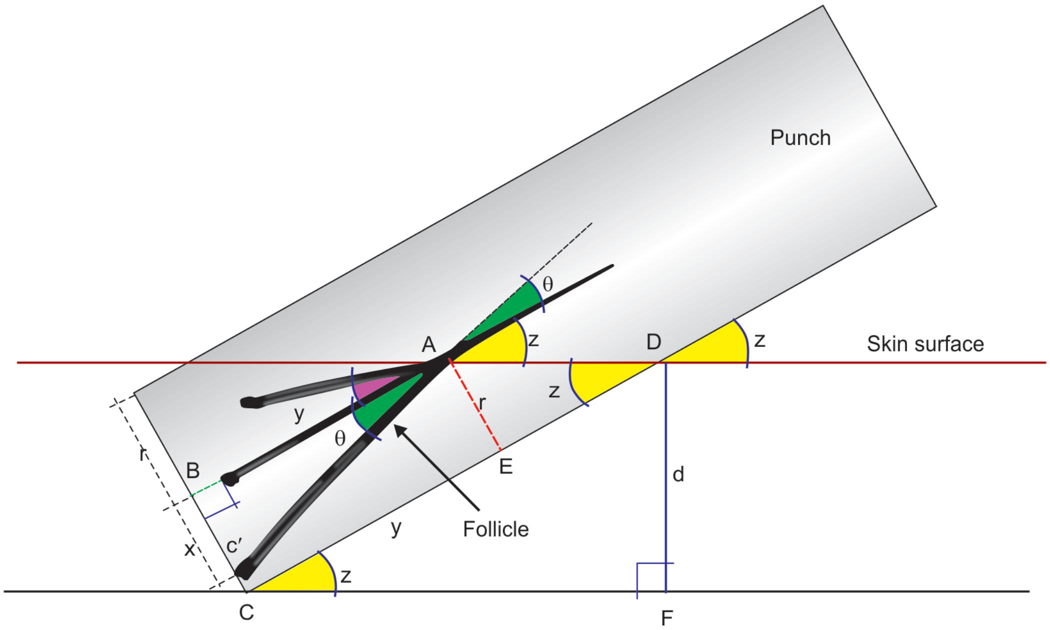


Figure 4.12

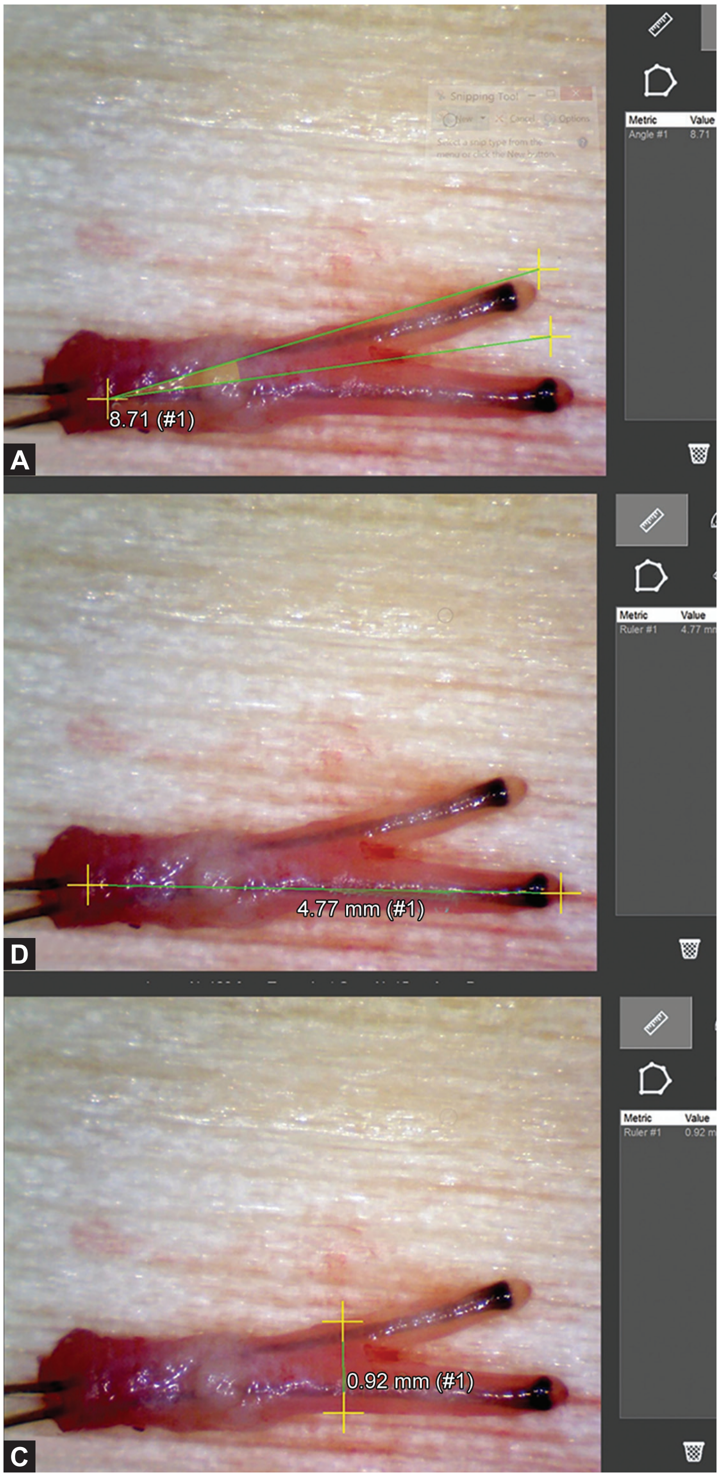
The diagram represents the cylinder of the punch during the extraction

In reality, however, Cole[1] demonstrated that it was harmful to the graft to penetrate with a sharp punch the entire length of the follicle when performing FUE with a sharp-punch system. Cole's concept of successful harvesting of grafts with a limited depth of dissection using a sharp punch does not require the punch to penetrate to the level of the dermal papilla. Additionally, limiting the depth of punch penetration will be different for each patient and even each hair follicle will have its own minimal depth of penetration needed for successful tissue dissection and harvesting.

I have previously explained that injecting intradermally 0.9% normal saline can modify the exiting hair angle of the follicles. So, the angle z increases up to 90°, making $\cot z = \cot 90° = 0$ and $\sin z = \sin 90° = 1$ (Figs. 4.7A and B). Then formula 4.6 becomes $x = 4 \tan \theta$. Therefore, if $\theta = 6°$, then $x = 0.42$ mm, which means that a punch size of 0.85 mm is the optimal choice.

In my daily routine, I do not need to make all these calculations because I use a system called Follysis that allows me to automatically measure all the important features of the FUs as previously referred to in this chapter. To that purpose digital images of the FUs are taken with a USB high-resolution camera at the beginning of each procedure. Figure 4.12 illustrates that the depth d of the FU is not equal to its length. I consider the minimal punch penetration depth to be approximately at or below the mid-portion of the follicle. Punch dissection must occur at or slightly below this level to successfully cut the arrector pili muscle and remove an intact graft. Accordingly, it is unnecessary for the punch to extend to the full depth of the hair follicle.

For example, in Figures 4.13A to C, there is an intact FU. Follysis found that after injecting intradermally normal saline, the maximal lateral offset x is 0.46 mm and the angle θ =8.71°, so a punch size of 1.00 mm in diameter is efficient.

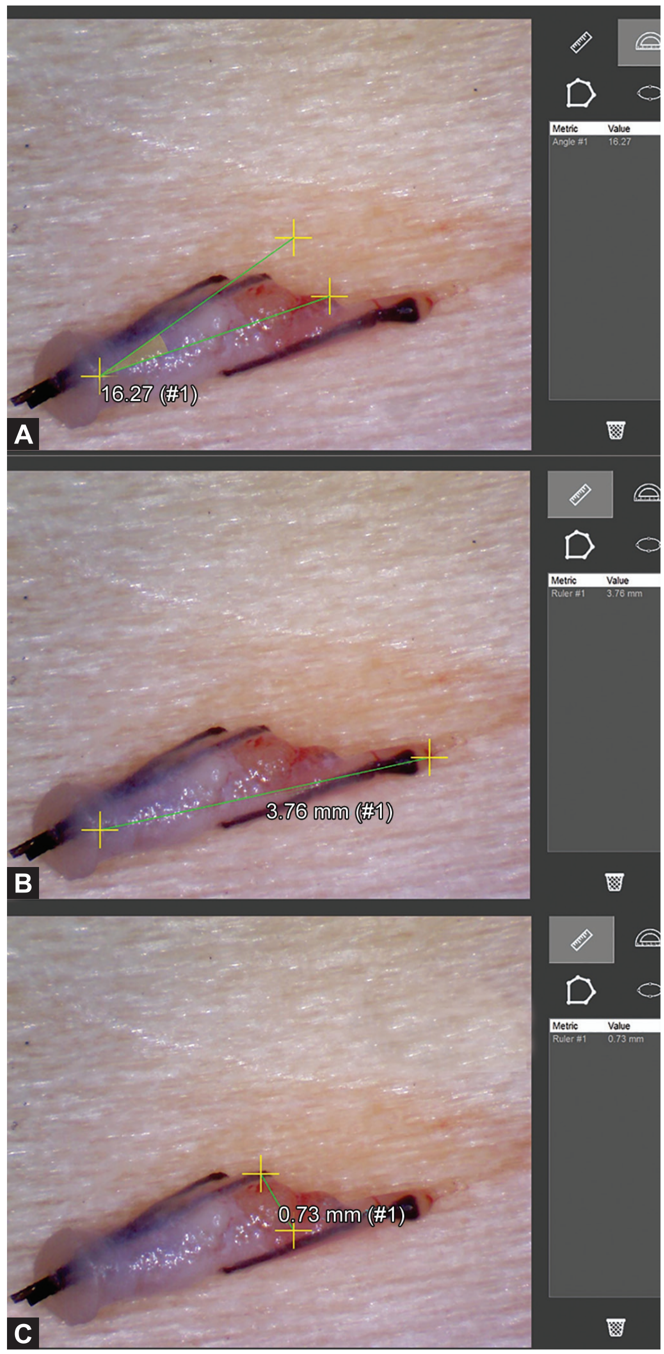


Figures 4.13A to C

Follysis records hair-shaft deviation at 8.71°, length at 4.77 mm, and lateral offset at 0.46 mm (normal saline was used)

As per formula 4.6, by injecting normal saline I alter the outgrowth angle of the FU making it easier for me to extract intact FUs by using a smaller-sized punch that creates less tissue damage.

In Figures 4.14A to C, the FU is seriously damaged because normal saline was not used and the image processing system recorded hair-shaft deviation at 16.27° and the latter offset at 0.73 mm. This means the choice of a wrong punch size was used.



Figures 4.14A to C

Follysis records hair-shaft deviation at 16.27°, length at 3.76 mm, and lateral offset at 0.73 mm (normal saline was not used)

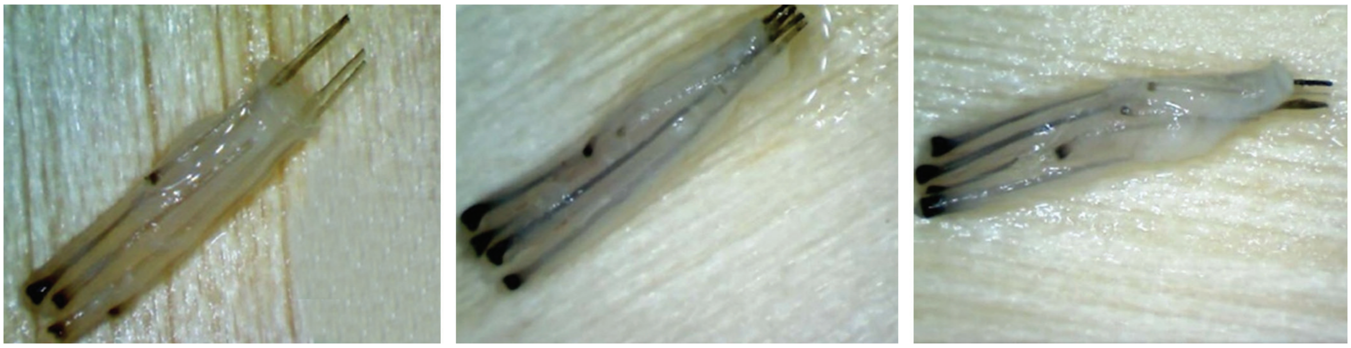


Figure 4.15

The image represents a unique look of grafts that contain 5-, 6-, and 7-hair follicles, respectively

Summary

The image processing system described is a tool for the physician to assist in the right choice of punch size while also reducing harvest transection rates. The processing system as a result decreases injury to the skin and allows for more efficient harvesting (Fig. 4.15).

THE MECHANICS OF FUE

A better understanding of FUE requires knowledge of the forces exerted on the punch, skin tissue, and the graft during the follicular-isolation procedure. Both mechanics and physics are involved in this process.

Because the punch motion is a compound one, it can be described simply in three steps:

1. The initial contact of the punch with the skin
2. The linear motion of the punch
3. The rotational motion of the punch

Let us examine each step in more detail.

When the physician places the punch edge at the surface of the skin, the cylinder of the punch should be aligned with the central axis of the FU. The axial force Fa applied by the physician on the punch is illustrated in Figure 4.16. We can consider that the weight force of the tool is negligible compared to other forces exerted on the punch. In this initial contact, the punch is in equilibrium, so the reaction force F from the skin surface exerted on the cutting edge of the punch is opposite to Fa. This force is analyzed into its component forces Fx and Fy.

If F_x is the horizontal force required for the punch not to slide, then the maximum friction that can be developed is equal to $T_m = \mu . F_{y.}$

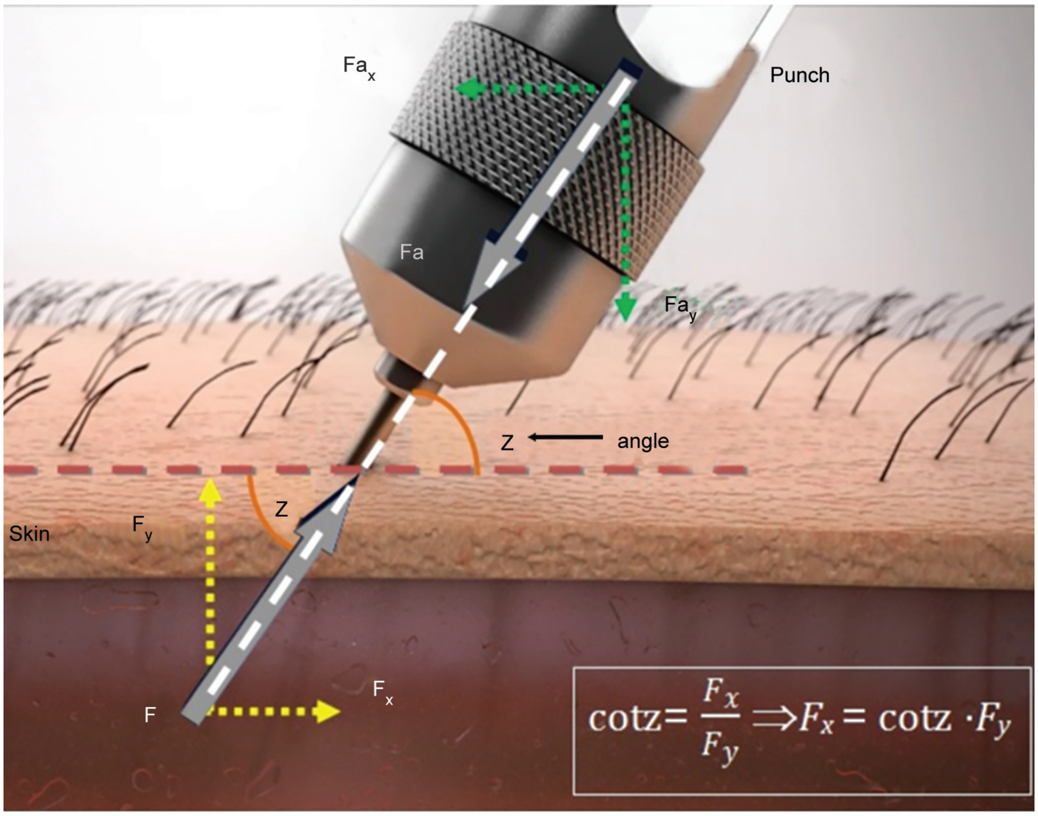


Figure 4.16

The forces exerted on the punch edge during initial contact with the skin surface

T_m is the maximum force of friction, which depends on the normal to the interface component F_y and μ_s is the coefficient of static friction.

The security margin $A = T_m - F_x$ is the difference between the maximal force $T_m = \mu_s \cdot F_y$ that can be developed by friction and the actual force F_x.

If $A > 0$, the punch will not slide. If $A < 0$, the punch will slide and transect the FU.

Therefore, the limiting condition is $A = 0$.

For the punch not to slide $A \geq 0 \Rightarrow T_m \geq F_x \Rightarrow$

$F_y \cot z \leq \mu_s F_y \Rightarrow \cot z \leq \mu_s$ (4.7)

where z is the angle between the punch and the skin surface.

So equation (4.7) proves that by measuring the coefficient μ_s of static friction, we can find the value of angle z where the punch does not slide.

At this point, I would like to clarify that the coefficient of friction expresses the frictional behavior that is defined as the ratio obtained by dividing the horizontal force resisting motion between two bodies and the normal force pressing the bodies together. This value depends on the properties of the skin, the contact material of the punch and its properties, the parameters of the contact between the materials, and the surrounding environment.

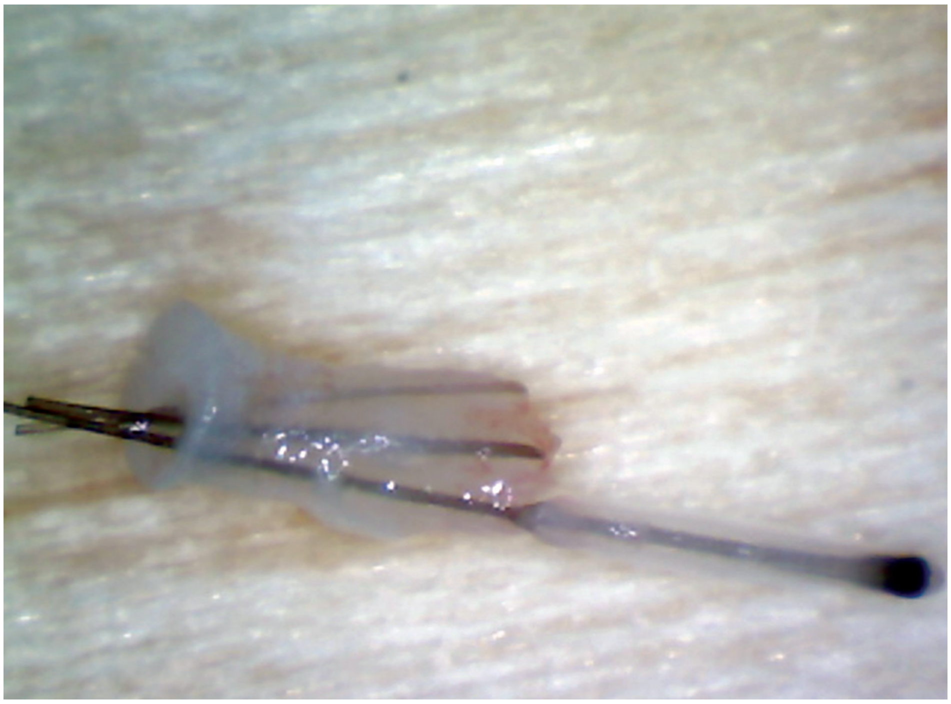


Figure 4.17

This microphotograph shows an eccentric cut on the surface of the skin due to a slip of the punch

Since coefficient of friction μ_s between skin and steel depends on the area of the body, the hydration and the skin temperature ranges from 0.8 to 1.

For example,

If $\mu_s = 0.8$, then $\cot z \leq 0.8 \Rightarrow \frac{1}{\tan z} \geq \frac{1}{0.8} \Rightarrow \tan z \geq 1.25 \Rightarrow z \geq \tan^{-1} 1.25 \Rightarrow z \geq 51°$

This means if the outgrowth angle is acute, there is a high probability that the punch will slide causing damage to the FU (Fig. 4.17).

By intradermally injecting normal saline, the angle z increases. Therefore, there is less danger of sliding.

The punch motion is a complex one that can be analyzed into two simpler motions: one linear motion and one rotational. Each one is independent of the other, so they should be studied separately.

The punch is driven by a main force to cut the epidermis and dermis. This force is a combination of an axial force F_a in the direction to the axis of the punch and a tangential force F_t, that rotates the punch.

The axial force is exerted on the skin at a certain angle z developing a stress

$$\sigma = \frac{F_a . \sin z}{S}, \quad (4.8)$$

where F_a is the axial force applied and S is the cross-sectional area of the punch wall given by $S = \pi r_1^2 - \pi r_2^2 = \pi (r_1^2 - r_2^2)$.

r_1= the outer radius and

r_2=the inner radius of the punch wall.

It is obvious that the thinner the punch, the smaller the S value, and the higher the σ. Furthermore, the higher the angle z, the higher is the stress σ.

When F_a is applied on the skin surface, it compresses and extends it until the value of σ exceeds the rupture stress of the skin (Fig. 4.18).

According to documented mechanical properties of human skin, the rupture stress of skin due to compression is higher than that due to tension, so two things may happen.

First, the surface of the skin is subjected to compression by the punch and is deformed. This results in a change of the follicle's position in the subcutaneous and dermal layers. Second, the tension force upon the skin moves the follicles away from the punch lumen.

Both cases lead to follicular transection. To offset this outcome, the punch is placed perpendicularly to the surface of the skin, which is now compressed by a larger axial force, reaching the rupture stress faster. In addition, if a sharp punch is used, the contact area is smaller, so the necessary rupture stress will be exceeded quickly, causing minimum deformation to the hair follicles, thereby reducing the transection rate.

After successfully cutting the epidermis and dermis of the skin, the proximal portion of the graft ends up in the lumen of the punch. The distal part is adhered to the adipose tissue, while the top base is subjected to a twisting movement, or torque $T = 2\,F_t\rho$. Where F_t is the tangential force exerted on the circumference of the part of the graft in the punch and ρ is the radius of the punch.

The torsional loading to a graft during punch rotation occurs because the proximal part of the graft is in contact with the inner surface of the punch (Fig. 4.19).

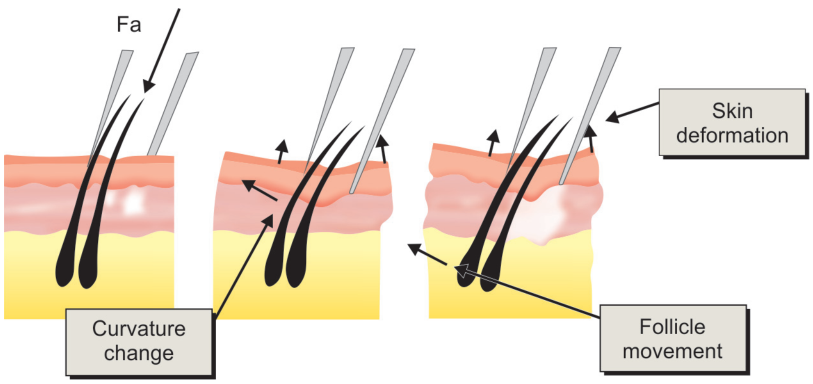


Figure 4.18
Deformation of skin and follicle geometry due to the application of force *Fa*

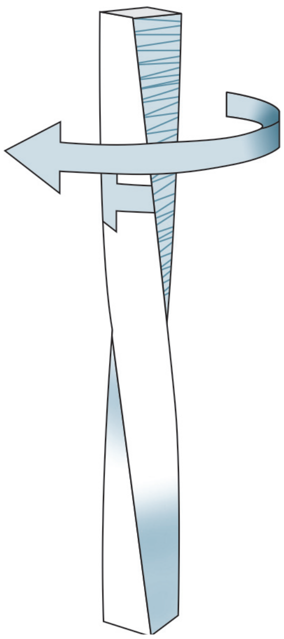


Figure 4.19
An optical view of a shaft subjected to torsional loading

Here I would like to make the following assumptions:

- The analysis of torsion of circular sections can be applied to rigid sections.
- The material of the FU is considered to be homogeneous.
- Torque is constant.
- Transverse planes remain parallel to each other.
- For small angles of rotation, the length of graft and its radius remain unchanged.

The shear stress τ is defined as

$$\tau = \lim_{\Delta A \to 0} \frac{\Delta F_t}{\Delta A}, (4.9)$$

which is the intensity of a shear force that acts parallel to the material cross-sectional punch. We call shear strain θ the deformation caused by shear stress.

Then it is proven that $\tau = \rho\ G\frac{d\varphi}{dx}$ (4.10)

which correlates the shear stress τ linearly to the radius ρ away from the center of the section. G is the shear modulus or modulus of rigidity, and $\frac{d\varphi}{dx}$ is termed as rate of twist, which is constant at any cross-sectional plane of the graft.

The last equation represents the shear stress distribution in circular section, which is higher at the outer surface of the graft (Fig. 4.20).

Another way of expressing this is by using the Engineer's Theory of Torsion.

$\tau = \frac{T}{J}\rho$, (11) where J is the graft's polar moment of inertia.

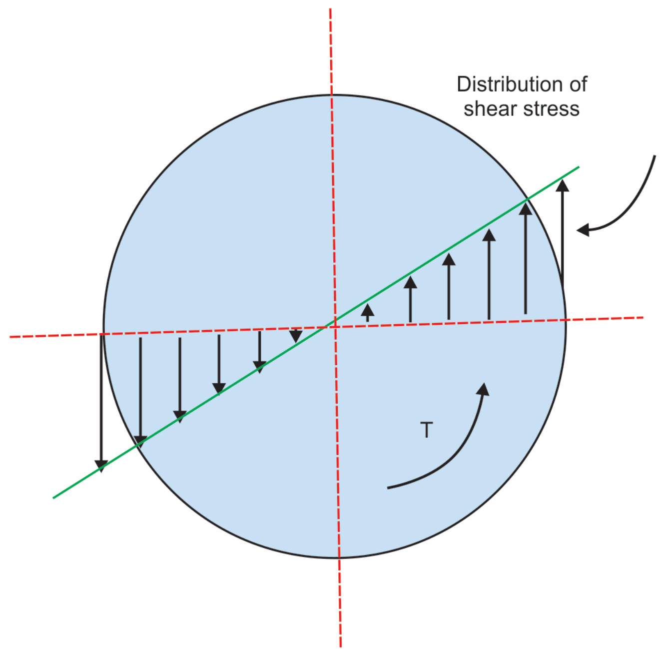


Figure 4.20
Shear stress distribution in circular section with applied torque *T*

Therefore, the maximal shear stress can be calculated as $\tau_{\max} = \frac{T}{J}\rho_o = \tau_f$ = shear stress of graft fracture where ρ_o is the radius of punch.

For given values of *T* and ρ_o, we can calculate τ. If $\tau < \tau_f$, then the graft will not be transected. But $T = 2\,\rho_o F_t$, so the higher the tangential force F_t, the higher the torque *T*. Consequently, the shear stress applied exceeds the maximum shear stress of the graft causing inevitable amputation of a number of hair follicles within the graft (Fig. 4.21).

Finally, I would like to emphasize how important the tangential force F_t is for the harvesting process. At the beginning of donor harvesting, the high value of F_t is beneficial during cutting of skin. However, if this force continues to be exerted at a high value, the outer structures of the follicle could be transected.

THOUGHTS AND PEARLS

In summary, the significance of image processing in my work enables me to accurately validate my theoretical predictions and use them for my FUE procedures. Most FUE surgeons may avoid the complex nature of medical physics. In order to assist the hair-restoration community to understand mathematical models, the following algorithm, Damage Algorithm, is described. This algorithm demonstrates how the exit angles of the emerging hairs potentially trigger a series of events leading to diminished quality of grafts, delayed healing process, and postoperative pain (Fig. 4.22).

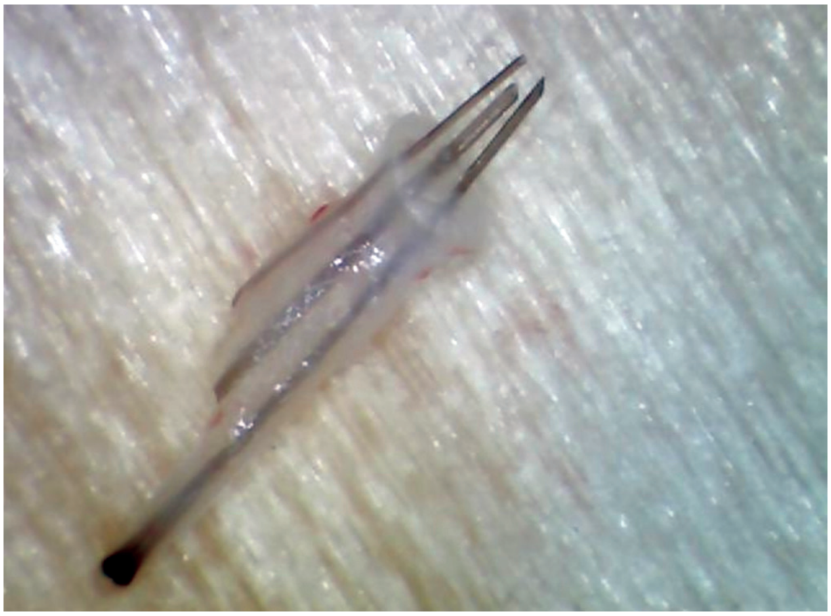


Figure 4.21

An amputated graft caused by excessive shear stress

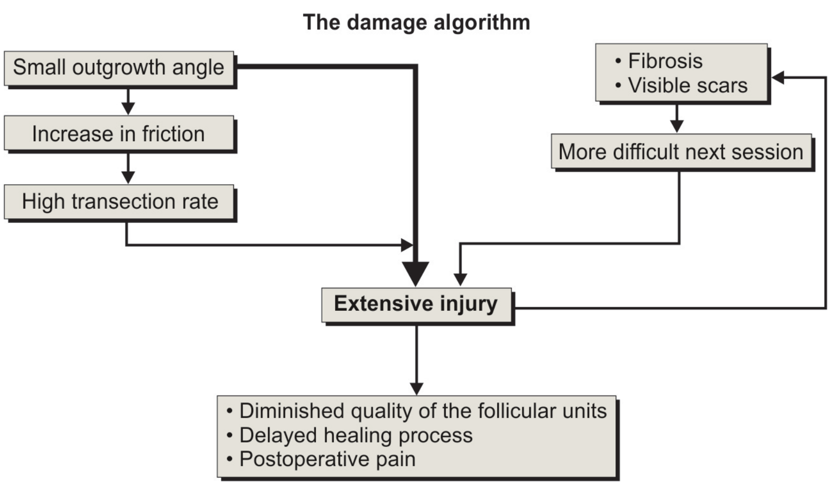


Figure 4.22

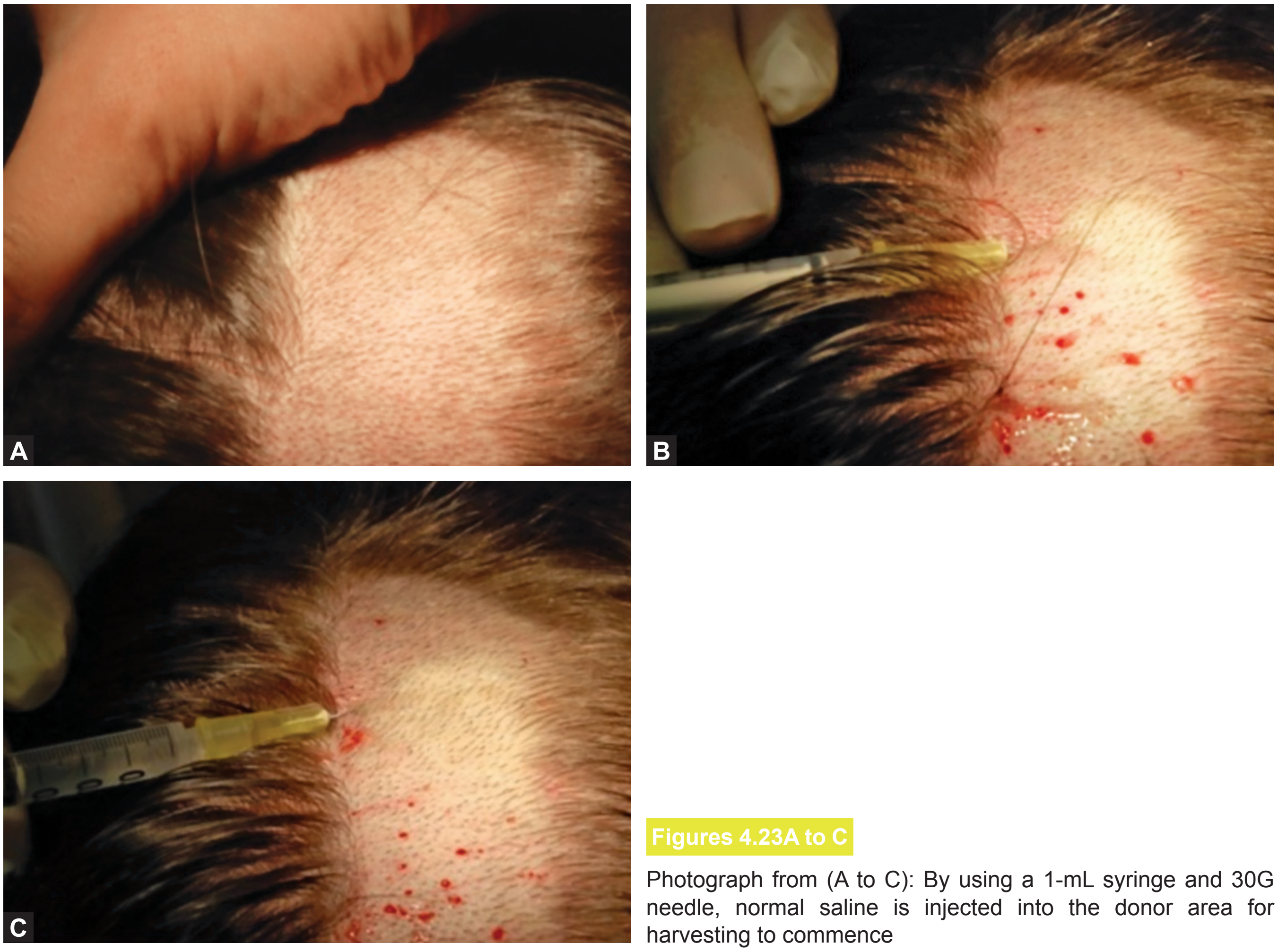
The Damage Algorithm shows how a small outgrowth angle dramatically affects the trauma to the donor area

Photo Courtesy: Adapted with the permission of Dermatologic Surgery from Zontos G, Rose P, Nikiforidis G. A mathematical proof of how the outgrowth angle of hair follicles influences the injury to the donor area in FUE harvesting. *Dermatol Surg*. 2014;40(10):1147-50

Following the damage algorithm, a smaller exit hair angle potentially increases the amount of trauma to the donor area because the punch directed at a steeper angle creates an elliptical wound that is significantly larger in surface area than if a more perpendicular punch is used. As the punch comes into contact with the skin and dissects through it and the dermis, the increased force of friction causes follicular displacement. The displacement or movement of the follicles potentially increases the transection rate in the hands of a novice or intermediate FUE surgeon. Potentially, an increased transection rate would contribute to more trauma in the donor area. As more harvesting attempts are required to obtain the desired number of grafts, one could theorize that scar formation or fibrosis from wound healing is increased. The possible consequence of extensive skin trauma is a donor site that may be compromised in future FUE donor harvesting.

The emerging exit angle of the hair influences the trauma caused by the punch in FUE harvesting. A steep angle or small exit angle potentially increases the injury to the donor area. To increase the exit angle of the hair shaft so that harvesting could be easier, simply injecting normal saline into the skin and dermis prior to harvesting will allow for a more obtuse angle of the hair follicles.

Additionally, the injection of 0.9% normal saline causes the direction of the hair follicles to be more predictable (Fig. 4.7) and the skin turgor, firmer. Figure 4.22 shows a small angle that increases high transection rate. A larger exit angle tends to make the harvesting process easier and reduces the transection rate, thereby assuring that more intact grafts can be extracted as formula 4.6 demonstrates. I suggest that 0.2–0.3 mL of normal saline per square centimeter of donor area should be injected intradermally into a small section (approximately 8 cm^2) of the donor area for harvesting to begin. Depending on how quickly the normal saline diffuses from the tissues, this process is repeated either in the same region or in a new part of the donor area until the desired number of FUs is obtained (Fig. 4.23).



Figures 4.23A to C

Photograph from (A to C): By using a 1-mL syringe and 30G needle, normal saline is injected into the donor area for harvesting to commence

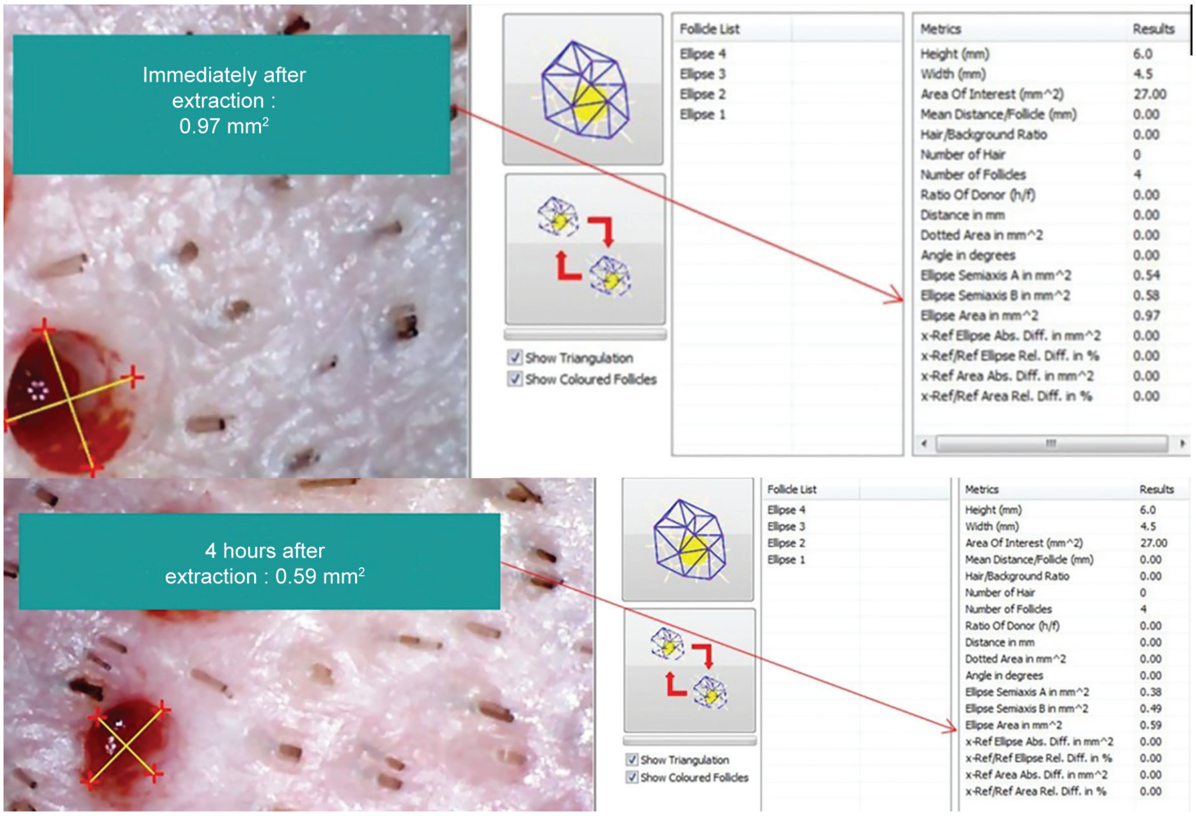


Figure 4.24

Follysis calculates a 39.18% decrease in surface of the wound 4 hours after the extraction

By injecting normal saline into the dermis, the skin naturally stretches. The skin and dermal anatomy return to normal when normal saline has been systemically absorbed or diffused away from the tissues. Thus, the surface area and dimensions of the surface of the wound are further reduced (Fig. 4.24).

This important fact results in accelerating the healing process, decreasing the degree of scarring, and minimizing any possible blood loss. The latter has motivated me to continue my research on the applications of medical physics in FUE with Follysis.

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