

Medical Device for Automated Prick Test Reading

Xabier Justo, Iñaki Díaz, Jorge Juan Gil, and Gabriel Gastaminza

Abstract—Allergy tests are routinely performed in most hospitals everyday. However, measuring the outcomes of these tests is still a very laborious manual task. Current methods and systems lack of precision and repeatability. This work presents a novel mechatronic system that is able to scan a patient's entire arm and provide allergists with precise measures of wheals for diagnosis. The device is based on 3D laser technology and specific algorithms have been developed to process the information gathered. This system aims to automate the reading of skin prick tests and make gains in speed, accuracy and reliability. Several experiments have been performed to evaluate the performance of the system.

Index Terms—Prick test, wheal, automatic measurement.

I. INTRODUCTION

ALLERGIES are common diseases for all age groups worldwide. In the developed world, about 20% of people are affected by allergic rhinitis [1] and about 6% of people have at least one food allergy [2].

At present, the most commonly used method for detecting allergies is known as a prick test [3]. The test consists of applying a small amount of allergen to the skin of a patient, usually on the inner forearm (Fig. 1a), then making a micro-incision in the skin with a small lancet, thereby bringing the allergen in contact with the body (Fig. 1b). As a consequence, a small allergic reaction may arise in the form of a wheal or papule (Fig. 1c), whose size and shape determine the degree of sensitivity. In a next step, between 15 to 20 minutes after puncture, a doctor or nurse marks the contour of the wheal with a pen so it can be measured (Fig. 1d). This method is often applied simultaneously with different allergens, thereby making it possible to test multiple allergies.

The prick test method is relatively simple and fast. However, the analysis and measurement of the size of the wheals that correspond to a positive reaction are performed in a completely manual manner. No standardized automated system exists for recording and interpreting skin prick tests. Moreover, the measures obtained from the test show great variability due to the difficulty of marking and precisely measuring the contour of the wheal [4], [5]. Besides the reading, there are other sources of variability in the prick test.

Knowing what to measure is as important as the measurement itself [6]. In general, two main parameters are used [7]: the maximum diameter (or the mean diameter) and the area, which shows less variability [8]. Results have to be interpreted by the allergologist, and such interpretations are not exempted

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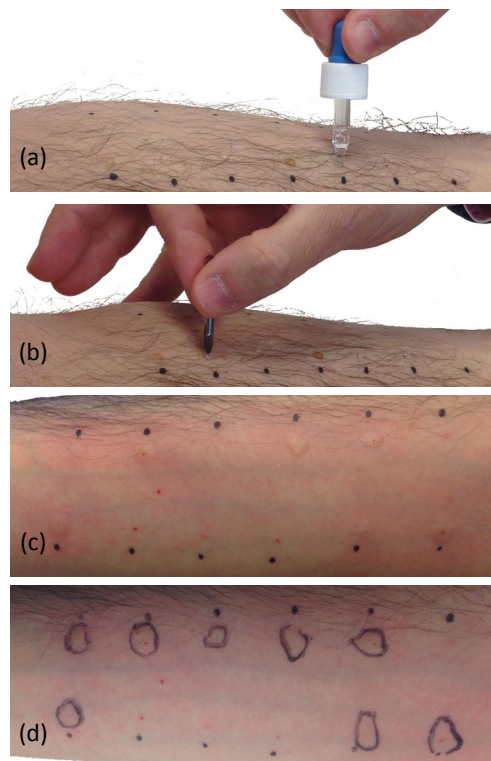


Fig. 1. Prick test usual procedure: (a) allergen deposition, (b) puncture with an ALK lancet through the drop of allergen, (c) allergic reaction after 15 min., (d) wheal contour marked with a pen to measure the area and/or diameter.

from additional variability. It has been shown that the same contours can elicit different conclusions among experts in the field [4], [5], [9].

As a consequence of all the above, the field of Allergology faces an important challenge when it comes to researching a proper method to standardize the results. This paper presents a novel machine that allows allergic reactions to be measured automatically and with precision. The system is based on laser technology, which reconstructs the geometry of the arm. This is followed by a new methodology that has been developed to find the wheals and calculate their shape and size [10].

The rest of the paper is organized as follows: Section II reviews the state of the art in similar technologies, Section III describes the device in detail, and Section IV presents the methodology implemented to compute the wheal properties. Section V validates the whole system by performing several tests. Finally, Section VI discusses the conclusions and future work.

II. STATE OF THE ART

A method currently used to measure the size of a wheal is to first use a pen to mark the wheals that emerged during the

prick test (Fig. 1d). This mark is then collected by placing a piece of transparent adhesive tape on the mark so that the ink adheres to the tape. Then the piece of tape is placed on a graph paper, usually in an area of the paper that identifies the corresponding allergen. Afterwards the number of squares that the maximum diameter of the wheal occupies is calculated and written down. These results are then given to the doctor, who determines a suitable prescription.

In an attempt to automate this process many systems and technologies have been developed in recent decades [11]. Here we pay special attention to those systems based on photography and 3D scanners.

Measuring wheals by using a digital camera started in 2005, when Suchecki et al. [12] decided to place a 3.2 megapixels resolution camera above the forearm or the back of four patients. In their work two types of illumination were analysed: an halogen lamp and a bulb, as these are the most common illumination types currently used in hospitals. After capturing the forearm or the back of the patient, the RGB (Red, Green, Blue) components were transformed into HSV (Hue, Saturation, Value) format. With this data, a first filter was applied to reduce the usual noise due to other protuberances that were not wheals (e.g. hair, veins). The area of the wheal was then estimated using the HSV colour space and the H component, generating binary images. A sum of the positive pixels was computed in square millimetres, and from that the area of the allergic reaction was obtained. As a general conclusion, Suchecki emphasized that illumination was key, and that filtering is needed to avoid the noise around the wheal and obtain the correct contour.

In 2007, dos Santos et al. [13] proposed a new method that used an Olympus 650C camera and the tests were run on 80 volunteers (31 men and 49 women) aged between 4-67 years. Reagents were histamine (10 mg/ml), Dermatophagoides pteronyssinus extract or saline solution. Illumination was provided by two photo-flood lamps and Adobe Photoshop[®] was used to apply two types of filter: a plastic wrap and a poster edge. The number of pixels inside the obtained contour were summed to yield the total wheal area. Results were compared with more conventional measuring systems, such as mean diameter (longest diameter and mid-point orthogonal diameter) and contour scanning. Positive reactions were considered to be above 12.48 mm² as a consequence of hardware limitations, resulting in a detection rate of 87.2%. Intra- and inter-observer variance was measured as 0.53% and 5.95% respectively. Among the various conclusions, one of the more important ones is to have good lighting while taking the photo.

In 2008 the same authors tested another method, using a different system, namely the 3D scanner [14]. They used a commercial system (PRIMOS 5.075D) which automatically determines the size of emerging volumes. This system flattens the surface, so that unusual volumes are easily read. Allergic reactions were scanned by two operators in a test that was identical to the previous one. Moreover, prior to the real tests the machine was calibrated as well as along those tests, to ensure the accuracy before and in long-term. Results were compared with traditional measuring systems, such as mean

diameter. For the calibration test, a model of a 50.27 mm² area was used and compared with the two operator readings: 49.92 ± 0.20 mm² and 49.90 ± 0.16 mm².

In 2011 Huttunen et al. [15] tried a different approach. They identified the key problem as being the poor contrast between wheal and skin. To avoid this, pictures were smoothed, mapped into grey-scale and transformed to two colour spaces: HSV and L*a*b* (L* Lightness, a* and b* colour scale in 2D). To detect the wheal, the user specified its approximate middle point, and the algorithm obtained a set of RGB values in a 10 pixel radius, and another set in a 45 and 50 pixel radius. After performing several operations, the most probable contour was obtained, and an ellipse was positioned on top of it, fitting the contour. The area of the fitted ellipse was computed in order to obtain the wheal area. Results were not promising as the wheal could not be idealized in an ellipse shape.

In 2014 Bulan [16] made use of a smartphone camera for wheal detection. Four points were located on the forearm, forming a square. The points defined the area of interest, but they also served as a reference to correct the camera lens distortion and tilt angle. Illumination variances were avoided by transforming the images to the YCbCr colour space (Y luminance, Cb and Cr chrominance) and discarding the Y channel. Operations over the Cb and Cr channels led to a better contrast picture, which made it possible to perform morphological operations and obtain the wheal contour. Experimental results did not include area determination; only the presence or absence of wheals was detected.

3D imaging is also used in other medical areas. In 2002, Friedman et al. [17] used the same 3D scanner as dos Santos to digitalize the surface of a face in order to have an objective measurement of its roughness. The purpose of the study was assess different facial treatments. Later, Rosen et al. [18] used a similar system to obtain the 3D surface of determined areas in order to have a record of human skin diseases, such as melanomas or dehydration. In 2013 Min et al. [19] used surface imaging to control the skin lesions caused by acne. In this case, the main objective was to count protrusions rather than each lesion area.

To the best of our knowledge, there are no articles in the literature that presents a system that is able to automate the process of measuring the outcomes of a prick test in a fast, reliable and accurate way.

III. HARDWARE DESCRIPTION

This article presents a novel device (Fig. 2) in an attempt to solve the aforementioned technological challenges. The cover is made mostly of plastic, as this material is widely used in current medical machines. The ease of handling plastic makes it possible to create a model that adapts to the shape of the arm, so that the arm's position is acceptable for both reading and the patient.

The system has an arch, which is supported by two bars that have bushings on each side. The arch is actuated with a stepper motor and a pulley-belt transmission that allows linear displacement. The motor is isolated from the system in order to reduce vibrations. A 3D laser camera (Vision Components



Fig. 2. Device for automated prick test reading developed at CEIT.

device, nano 3D model, yr1230 series) is located in the upper part of the arch (also referred as head). This system features a 2M class laser (which does not need to be covered as a direct impact with the eye does not occur) with a wavelength of 660 nm and 30 mW of power.

The integrated 3D camera emits a laser beam as a line on the object to be scanned, and by using a two-dimensional sensor the reflection of that projected line is collected (Fig. 3). By knowing both the angle and the distance, it is possible to determine the parametric form of the line. By repeating this process several times a three-dimensional surface is obtained from the scanned object.

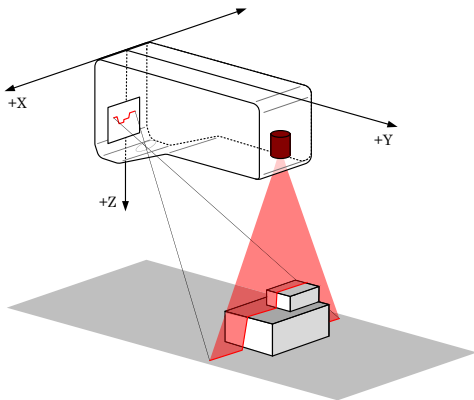


Fig. 3. Schematic of the 3D laser camera operation.

Unlike the usual operation of photographic cameras, the two dimensions of the sensor are not used to take a picture. For each pixel across the width of the sensor (X axis), the height (Z axis) represents the distance between the laser module and the surface of that point. This noticeably reduces the amount of data necessary to form the three-dimensional surface.

The range of the 3D scanner is not square; instead it takes the form of a truncated triangle. This is because the intersection of a pyramid (which is how a regular camera would take a picture) and a non-orthogonal plane results in a different geometric section. The internal electronics of the system takes this phenomenon into account, but it is a factor to keep in mind when selecting both the range and the horizontal resolution, since the resolution varies with altitude.

The assembly is controlled by software installed on a WiFi-connected computer. The core chip in the device is an Arduino Yun with a dual processor, one for managing the stepper motor (ATMEL ATmega32u4) and one for managing communications between the 3D system and the computer (Atheros AR9331). The motor controller features an Allegro A4983 chip set to power the stepper motor. The system is powered up from a single power supply of 24 V and 5 V.

The general operation of the device is as follows: once the allergic reactions have arisen (15 minutes after puncture), the patient is asked to put his or her arm on the device as shown in Fig. 2, so that the inner part of the forearm is facing the camera. Then, the nurse activates the scanning process from the computer. The head will then move over the length of the arm at a constant speed while the camera records the surface of the forearm. The full displacement lasts 10 seconds. Once the predefined distance is completed, the head returns to its original position and the patient can remove his or her arm. Meanwhile, the program installed on the computer analyses the surface and displays the information for each wheal found.

IV. WHEAL DETECTION AND MEASUREMENT

This section describes the methodology developed to identify and compute the area of the wheals detected on a patient's arm. First, we show how to define the optimal resolution for the system, which directly impacts the accuracy of the results as well as the amount of data managed and processed. In a further step, the patient's arm is reconstructed and a filter is applied in order to subtract the volume of the arm and only leave the allergic wheals or possible candidates. The final step consists of locating the wheals and discarding other elements (veins, etc.) and then computing the area of the detected wheals.

A. Resolution

The resolution of the 3D camera has a direct effect on the precise detection and computation of the wheal area. Allergic wheals usually have an ellipsoidal cap shape, which produces an elliptical area. In order to determine the precision needed to calculate the area, we consider a circle as the base area of the wheal. As can be seen in Fig. 4, a square that is 3 mm in size is represented with a circle inside of it, which represents the contour of a wheal. The device is set to have the same resolution in both the X and Y axes. This is achieved by matching the speed of the head in the Y direction so it coincides with the resolution in the X direction (e.g. moving the head at 6 mm/s and acquiring data at 80 Hz). Thus, each point detected is equivalent to a square pixel.

If the different heights that are captured are organized in a matrix, each of the values represents a full squared pixel. As it is impossible for the pixels to match the exact area of the wheal, differences will occur between the real area and the digitalized one. Therefore, to obtain the maximum error that can occur as a result of this effect, the difference between the exact area of the circle and the quantified area using squared pixels is calculated. As the maximum error that can occur depends heavily in the circle positioning, the circle is moved

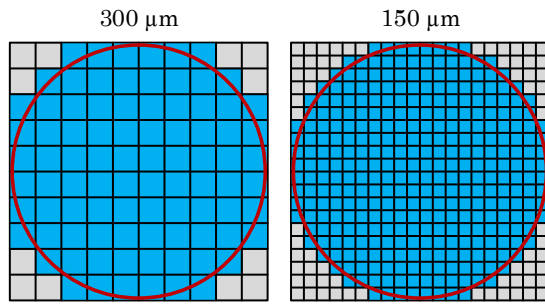


Fig. 4. Example of two circles read at different resolutions. 300 μm resolution on the left, 150 μm resolution on the right.

half a pixel in both directions in several steps to obtain the maximum error.

TABLE I
THEORETICAL ERRORS FOR THE MEASUREMENTS OF THE WHEEL AREA FOR DIFFERENT LASER RESOLUTIONS

Resolution (μm)	Profile area (mm^2)						
	4.988	7.069	10.010	14.999	20.030	24.983	29.996
75	0.87%	0.90%	0.48%	0.36%	0.23%	0.24%	0.29%
150	2.56%	1.64%	1.77%	1.59%	0.92%	0.87%	0.51%
300	6.46%	5.78%	4.30%	6.21%	2.94%	2.31%	2.31%
600	20.6%	18.5%	15.1%	8.01%	6.54%	4.90%	6.81%

Table I shows the theoretical precision that would be obtained with different resolutions and circle sizes. Resolutions of 75, 150, 300 and 600 μm are studied, and also different areas ranging from approximately 5 to 30 mm^2 . Given the aims of this article, an error below 10% for wheals greater than 10 mm^2 will be chosen as a starting point, which is far beyond current manual accuracy. This determines that the resolution should be at least 300 μm .

To determine the required resolution in the Z-axis, it is only necessary to read the bumps that oscillate around the usual thickness of a wheal. An allergic reaction is typically between 0.1-0.5 mm thick, so a resolution of 50 μm would be enough to detect the minimum height of the range.

B. Data Processing

Once the patient's arm is read at the specified resolution, the volume can be reconstructed with the distance points gathered. The next step is to isolate the protuberances. To that end, removing the curvature of the arm is the most important part of data processing prior to analysing the surface and looking for wheals. As the forearm has a significant curvature, it is difficult to determine the exact height of the different bumps on the patient. This is coupled with the fact that the curvature does not remain constant along the arm (Fig. 5 left).

To cope with this problem, the literature proposes a double reading strategy. It consist of a pre-test reading to have a model of the arm, and a prick test reading of the arm, so that subtracting one from the other should give just the wheals. However, it is very difficult for the patient to place the arm in the same position. Moreover, it is also required that the deformation of the arm be exactly the same.

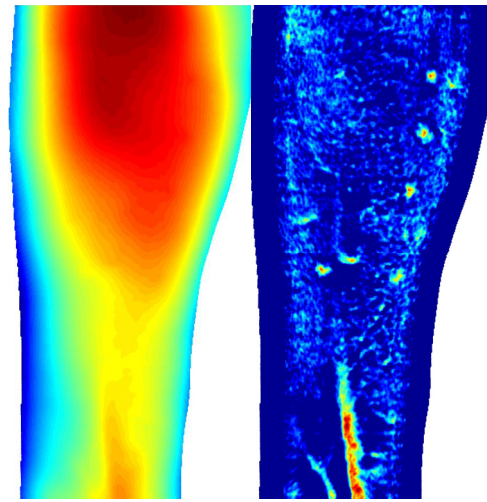


Fig. 5. 3D image of a human arm obtained by the 3D laser camera (left) and after subtracting the baseline with a median filter of order 30 for a system set to 300 μm resolution (right).

We propose doing only one unique reading after the prick, then applying an appropriate mean filter of high order (25 in most cases) to eliminate the various protuberances of the forearm while keeping the general curvature of the arm. Thus an exact model of the surface of the patient's forearm can be obtained, theoretically without any allergic reaction. And since reading is performed only once, both the position and the shape of the arm are identical in both cases. Once both surfaces (the original and the filtered one) are obtained, it is only necessary to subtract one from the other to remove the volume of the patient's arm, and as a result we get the different bumps without the general shape of the forearm (Fig. 5 right).

C. Wheal Identification

The surface obtained in the previous subsection includes bumps due to wheals, hairs, wounds, etc. Therefore, it is necessary to study all the irregularities founded in order to determine the ones that could be allergic results. The proposed strategy first detects a possible location where a wheal could appear and then analyses it to determine whether or not it is a wheal.

1) *Location*: The most common layout for the various allergens dispensed in the prick test is two columns: ulnar and radial. A nearly constant distance is easy to observe on the Y-axis (longitudinal), while it is more difficult on the X-axis (cross), as the width of the arm is irregular (Fig. 6). This means that the rows are regularly distributed on the forearm, while the distance between columns in each row varies. For this reason, we decided to study each axis separately.

The position of the rows ($Y_1, Y_2, \dots$) are located by finding the local maximums in a vector that contains the projection of all matrix rows in a unique column vector. For the X-axis the methodology applied is the same, but instead of projecting the whole surface, only a portion around the selected row is projected. Using this method, the doctor has the freedom to place the allergens manually and not in exact position while the number of points to study is reduced.

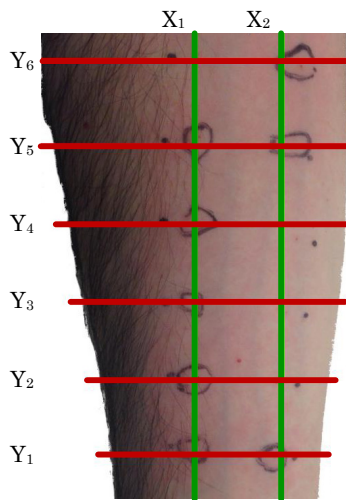


Fig. 6. Segmentation of the arm for obtaining the wheal search points.

2) *Filter Order Determination*: As section IV.B showed, high order filters are used to obtain a “clean” surface of the patients forearm, thus obtaining bumps on it by subtracting it from the original surface. This process gives us enough accuracy to search for bumps, but the order of filtering required is not known in advance. This order is set by an iterative process.

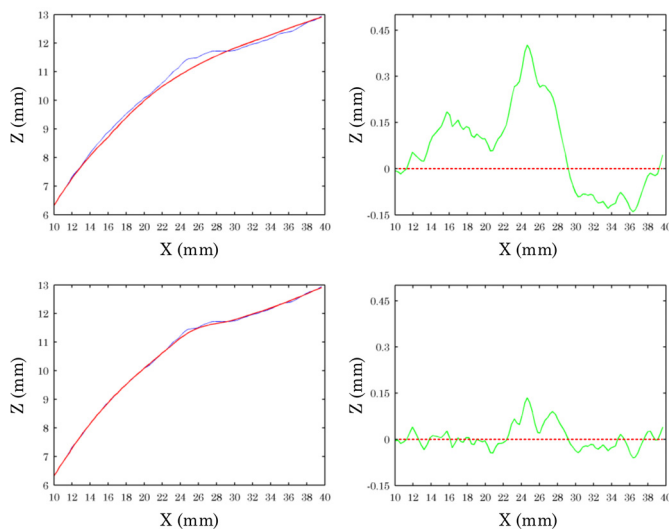


Fig. 7. Profile of an over-filtered surface (upper left) and the subtractions of the two surfaces (upper right). Profile of an optimum filtering (bottom left) and the subtraction of the two surfaces (bottom right).

When excess filtering is applied to the surface of an arm, two mountains appear. This effect can be easily seen in a section containing a protuberance (Fig. 7, top). If the filtering order is too high, the curvature of the arm is also filtered, creating a base surface that still keeps some original volume of the arm. As a result, the surface obtained does not represent the actual shape of the wheal. It will be necessary to match the filter order with the curvature of the arm at that point and for that bump in particular. Therefore, the order of the filter will be reduced until the joint between the protuberance and

arm has a Z-value equal to 0. This parameter will allow the iteration to stop. In reality, a Z value of 0 will be impossible to reach, so a window of 100 μm is considered to end the process.

As made evident by the process, the first filter step must be well above the optimum. In the case of insufficient filtering, the minimum shown in Fig. 7 (top) would be lower than 0, as shown in Fig. 7 (bottom), and there would not be a reference height to minimize. It is therefore considered the case of the largest wheal possible, and a filter capable of removing the curvature of the arm is calculated. This is defined as a starting point for the iteration. Steps are calculated dynamically depending on the height of the joint between the wheal and arm as defined by

$$f_{new} = f_{old} - 100 \cdot (h - 0.1), \quad (1)$$

where f is the filter order and h is the contour height in millimetres. It should be noted that this iterative process must be repeated for each of the points that emerged from the previous step.

3) *Area Determination*: To calculate an area from a surface, an intersection is made between a horizontal plane and the protuberance, obtaining a closed contour. As the surface obtained by the 3D laser camera is defined by points that form squares, the resulting contour will be polygonal. To calculate the area of such a polygonal closed contour, the Trapezoidal Rule method is applied. This method calculates the area with the 2D coordinates of the polygon edges as

$$\text{area} = \left| \frac{1}{2} \sum_{i=1}^n (x_{i+1} - x_i) \cdot (y_{i+1} + y_i) \right|, \quad (2)$$

where x and y are the 2D coordinates of each point of the polygon and n is the number of points that define it. Note that x_{n+1} and y_{n+1} are equal to x_1 and y_1 respectively, as the contour is closed.

To obtain maximum and minimum diameters, the contour is modified such that its points are distributed equally. This modified contour is only used for measuring diameters, and not for area calculations. Once the points are equally distributed along the contour line, the distances between points are calculated in order to obtain the maximum diameter of the wheal. For the minimum diameter, the minimum distance is not considered. As was shown in Section II, allergologists consider the minimum diameter as the mid-point orthogonal to the maximum diameter. Since the points are evenly distributed, half-way points between those obtained for the maximum diameter are taken, giving as a result the mid-point orthogonal diameter.

To determine the area of the wheal, another iterative process is proposed (Fig. 8). The start point for the intersection is the top most part of the wheal, and as the iterative process continues the intersection point will decrease.

There are two more objectives to accomplish. The first and simplest is to create a closed contour, at the end of the iteration as well as at each iteration step. This ensures that the lump is not a vein, tendon, or any kind of anomaly, and it does not allow the adhesion of adjacent protuberances.

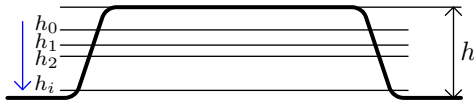


Fig. 8. Area calculation process, starting at h height and lowering the cutting plane in a iterative process.

The second objective refers to the shape of the protuberance. To understand this concept it is necessary to imagine that a possible wheal begins with a relatively large area on top. This area increases as the iteration steps decrease in altitude, but this increment is not arbitrary. For each iteration the progression of the area is calculated. This progression can be defined as

$$\text{progression} = \frac{\text{area}_{\text{new}} - \text{area}_{\text{old}}}{\text{area}_{\text{old}}} \quad (3)$$

This should decrease gradually, because a wheal has a similar area on the top and at the bottom. As the contour obtained reaches the bottom part of the wheal, the calculated progression is triggered and can be determined that the base has been reached.

V. VALIDATION

The validation of the system was carried out in 3 steps, with the intention to validate each decision taken in the previous section. The first set of experiments will validate the resolution chosen for the 3D system. Afterwards, another set of experiments will be conducted to validate the algorithm implemented to calculate the area. Finally, some tests with patients will be conducted to perform a preliminary validation of the whole system.

A. Resolution Validation

To validate the selected resolution (300 μm) a reference should be defined. To this end, an aluminium plaque was manufactured with different circumferences machined over it, ranging from 5 mm^2 to 200 mm^2 (Fig. 9). The plaque is manufactured from a ground rectified 8 mm thick plate. Protrusions that represented artificial wheals were machined on a CNC milling centre by side-cutting. To avoid occlusion when projecting the laser beam onto the plaque a chamfer was made at the upper edge of each circle. All the bumps are machined with a height of 300 μm . Finally, after machining, the plate was subjected to a sandblasting to get a matte finish and avoid excessive brightness when scanned. All protuberances were measured by a profilometer to obtain their real area.

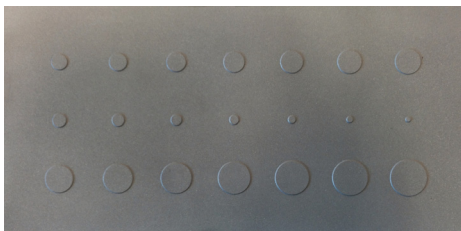


Fig. 9. Machined aluminium plate used to validate area calculations.

Once the actual area of each artificial wheal was determined, the results of the various resolutions were recorded. Table II shows only small bumps (approximately 5 mm^2 to 35 mm^2), where reading errors are greater (a pixel difference can make a bigger error when referring to a small area than to a larger one). Each wheal was scanned five times with the plaque in different positions and at different times of the day. For each reading, the data was obtained at full resolution (75 μm); later we truncated the data and got the four resolutions to study. For each resolution, pixels greater than 0.08 mm height were counted in order to avoid noise due to the 50 μm laser resolution, and a corresponding area for each pixel was applied, thus obtaining the total area.

TABLE II
MEAN ERRORS OF THE MEASUREMENTS OF THE AREA FOR DIFFERENT LASER RESOLUTIONS

Resolution (μm)	Profile area (mm^2)						
	6.674	8.696	12.851	17.814	23.179	28.795	34.005
75	3.9%	3.2%	2.8%	2.4%	1.9%	1.7%	1.5%
150	8.5%	5.8%	5.0%	4.0%	3.1%	2.3%	1.9%
300	11.0%	8.4%	7.2%	6.6%	5.5%	3.2%	2.9%
600	17.0%	13.0%	11.3%	10.6%	8.7%	4.8%	4.5%

As shown in Table II, the selected resolution (300 μm) is sufficient for meeting the objective of keeping the error below 10% for 10 mm^2 wheals.

B. Area Validation

Having selected the appropriate resolution, we proceed to validate the area calculation process using the same calibrated plaque. Since the correct area of each protuberance is known on the plaque, we can obtain the deviation of the measurement for each wheal size.

It should be noted that obtaining the area from a flat surface, from a tilted surface, or a curved surface are all different procedures.

1) *Flat Area*: To check whether the area was calculated correctly, we placed the plaque parallel to the 3D camera. Afterwards, we analysed five readings and obtained the maximum diameter, the minimum diameter and the area. They were compared with the actual measurements of each protrusion in order to obtain the deviation.

Table III shows the deviation for both diameter and area. It can be seen that the error decreases with the area and that for wheals with an area over 10 mm^2 the maximum error is below 10%, fulfilling the objective specified above.

2) *Tilted Area*: The tilt angle is defined as the angle between the plane of the plaque and the horizontal plane. This is intended to simulate wheals located in the ulnar or radial side of the forearm. Three angles will be studied: 10°, 20° and 30°.

As in the previous section, the maximum and minimum diameters as well as the area are analysed (Table IV). With this information we can compare the errors obtained with the errors in the previous subsection.

TABLE III
MEAN ERRORS OF THE MEASUREMENTS OF THE DIAMETER AND THE AREA USING THE DEVELOPED ALGORITHM

D _{max} (mm)	D _{min} (mm)	Area (mm ²)	Diameter Mean Error	Area Error
2.920	2.910	6.674	15.0%	19.3%
3.330	3.325	8.696	13.6%	9.0%
4.050	4.040	12.851	8.9%	7.7%
4.765	4.760	17.814	6.8%	5.2%
5.435	5.430	23.179	8.0%	3.7%
6.060	6.050	28.795	7.6%	3.4%
6.580	6.580	34.005	6.0%	2.4%
7.580	7.435	44.263	4.9%	3.3%
8.370	8.360	54.990	4.8%	2.7%
9.140	9.120	65.468	5.6%	2.0%
9.835	9.830	75.931	3.9%	2.7%
10.510	10.480	86.508	3.6%	3.2%
10.990	10.955	94.558	2.0%	3.1%
11.690	11.675	107.192	3.8%	3.7%
12.510	12.505	122.866	2.5%	3.2%
13.275	13.275	138.407	2.8%	3.1%
13.990	13.980	153.608	3.0%	3.1%
14.670	14.655	168.852	3.0%	2.6%
15.345	15.315	184.575	1.4%	1.0%
15.950	15.940	199.682	1.9%	0.9%
16.535	16.515	214.473	1.6%	0.9%

TABLE IV
MEAN ERRORS OF THE MEASUREMENTS OF THE DIAMETER AND THE AREA FOR DIFFERENT ANGLE INCLINATIONS

Angle	D _{max} (mm)	D _{min} (mm)	Area (mm ²)	Diameter Mean Error	Area Error
10°	2.920	2.910	6.674	17.5%	19.2%
	11.690	11.675	107.192	4.9%	3.7%
	16.535	16.515	214.473	2.6%	0.6%
20°	2.920	2.910	6.674	17.8%	21.8%
	11.690	11.675	107.192	7.7%	6.8%
	16.535	16.515	214.473	4.8%	2.5%
30°	2.920	2.910	6.674	16.7%	24.0%
	11.690	11.675	107.192	15.8%	12.0%
	16.535	16.515	214.473	11.4%	8.7%

No variation is distinguishable between the errors obtained for a horizontal plaque position and a 10° tilted position, while deviation increases for greater angles.

3) *Curved Area*: Unlike the plaque used in previous sections, patient's arms are curved. Therefore, it is necessary to check that the process of calculating the area remains valid in this case. A sticker was created and measured to obtain its real size. This sticker was applied on the exposed forearm of 14 volunteers, using the same sticker each time in order to reduce variabilities relative to the wheal model. To delete the uncertainty of the wheal tilt, this was placed in the centre of the forearm, as horizontally as possible.

The purpose of this validation was to determine the validity of the system when reading a wheal in normal use. The results are shown in Table V. The error rates are almost identical to

the percentages presented for the horizontal calibrated plaque. It can be concluded that the method presented for removing the curvature of the arm meets this objective.

TABLE V
MEAN ERROR IN THE MEASUREMENT OF A FAKE WHEAL PLACED ON A REAL ARM

	D _{max} (mm)	D _{min} (mm)	Area (mm ²)
Sticker	5.291	5.082	21.118
Trial 1	5.740	5.112	21.674
Trial 2	5.725	5.313	21.020
Trial 3	5.767	5.141	22.873
Trial 4	5.879	4.954	20.987
Trial 5	5.921	4.790	21.889
Trial 6	5.859	4.776	21.847
Trial 7	5.710	4.892	20.381
Trial 8	6.113	5.137	23.299
Trial 9	5.700	5.089	21.926
Trial 10	5.794	4.954	20.901
Trial 11	5.580	5.004	21.111
Trial 12	5.307	4.746	19.123
Trial 13	5.911	4.874	21.376
Trial 14	5.290	4.931	19.752
Error	8.4%	3.1%	3.9%

C. Preliminary Tests with Allergens

Finally, we proceeded to test the technology and the algorithms in a typical scenario. For this purpose, the conventional prick test was done with 35 volunteers and their arms were scanned. The tests were performed blindly, that is, the allergist stood in a separate room from the scanning device, and the person operating the system did not observe the allergen placing as well as the process of reading the arm. The process was as follows:

1. Record volunteer data (name, age, sex...);
2. Perform the prick test with random allergens, including saline and histamine;
3. Wait 15 minutes;
4. Read patient forearm with the new scan system;
5. Immediately have the allergist do a conventional reading with a standard test sheet.

Once the process ended, we proceeded to analyse the results of the system and compare them to the results provided by the allergist.

Fig. 10 compares for the same volunteer the outcomes of the system and the standard test sheet filled in by the allergist. The system was able to find and accurately compute the area and height of four wheals plus the histamine, but it also considered two additional enclosed protuberances as wheals (they met all the criteria specified in the algorithms). These positive matches were treated as "false positives".

Detailed results for all volunteers are shown in Table VI, where a minimum area of 10 mm² is the threshold for counting protuberances as possible wheals. The system detected 169 enclosed protuberances that matched the criteria for potential wheals. The allergist found 97 "real wheals", 94 of which were also found by the system. However, the system was able to

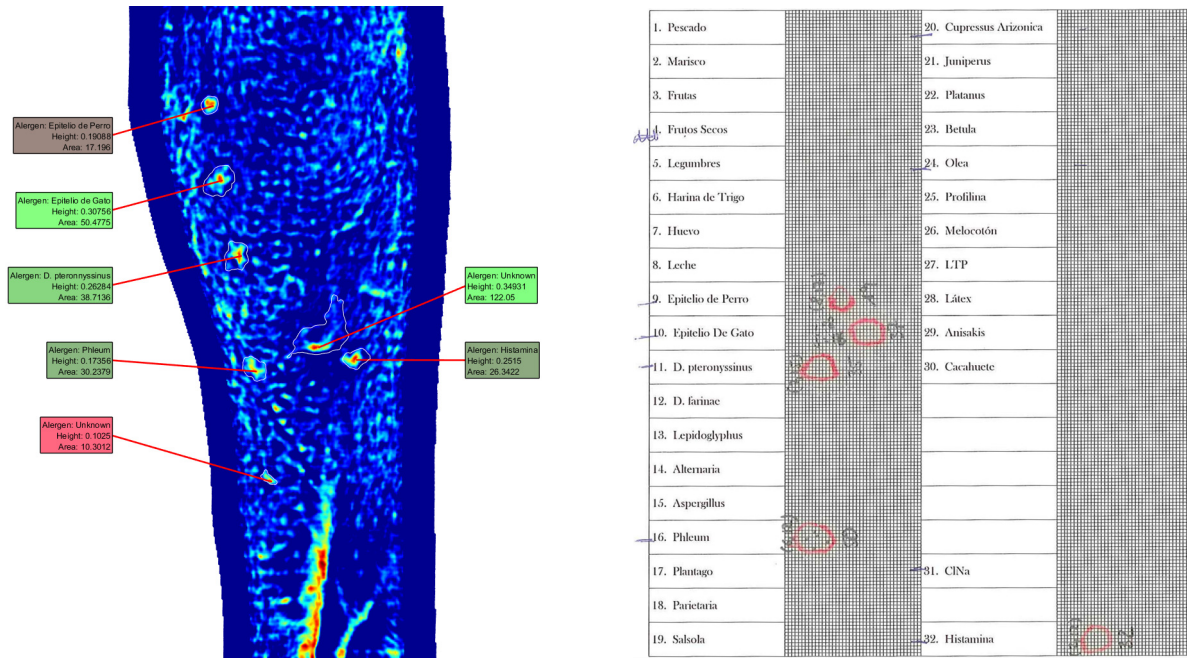


Fig. 10. Example of a test with different allergens administered to a volunteer. Left, a 3D image of the volunteer's arm with the detected candidates for allergic reactions as determined by the software. Right, the standard prick test sheet used by the Department of Allergology and Clinical Immunology (CUN, University of Navarra).

find 5 “new wheals” that the allergist did not find (or that he had not considered to be wheals since they had small areas close to 10 mm²). The remaining 70 contours detected by the system were “false positives”.

TABLE VI
RESULTS OF THE PRELIMINARY TESTS ADMINISTERED TO 35 VOLUNTEERS

Minimum Area Considered: 10 mm ²		
Contours Detected	169	
Real Wheals	97	
System Wheals	94	97% of the total
False Positives	70	41% of the total
New Wheals	5	

In general, the system performed very well, finding 97% of all real wheals. The system did miss a very small number of real wheals (only 3), but it found a number of wheals (5 in this case) that were not found or classified as such by the allergist due to their size. Regarding the false positives, these are in most cases related to veins, freckles, hair, etc. Further research will apply more intelligence and specifications to discard these cases (e.g. new geometric constraints, volume constrains, etc.). Additionally, we believe that building up a larger database of wheals will allow us to reduce the number of false positives to a minimum. Currently, the system allows the user to interactively discard these cases in the application.

To sum up, the system we have developed goes beyond the state of the art by providing allergists with a device able to find and accurately measure allergic wheals. It is able to report results within 20-30 seconds, a significant time gain over the current manual approach, which takes between 5-

10 minutes. Compared to other devices, it lacks limitations due to colour discrimination and lighting. It seems to perform well regardless of skin colour (one of the volunteers had black skin).

VI. CONCLUSION

A new medical device was developed to automate the process of reading prick tests, which currently is a manual and laborious task that lacks precision. The proposed system considerably simplifies the process and provides a reliable measure of the area of the allergic wheals detected, enabling a good diagnosis. The whole process, from reading the arm to outputting the results takes between 20 and 30 seconds, depending on the number of wheals to analyse.

The device consists of a 3D camera based on laser technology and a mechatronic platform that moves the camera along the patient's forearm. This work described the proposed mechanism in detail, as well as the methodology followed to compute the area of the wheals from the information gathered by the camera.

Several experiments were carried out to validate the implemented algorithms. First, a reference was created to measure the real precision of the system with confidence, and then experiments with real arms were presented. Tests were carried out with a resolution of 300 μ m, which yielded a precision error of 10% for areas of 10 mm². The system can measure the area of the wheals with an approximate error of 10% around 7 mm², 8% around 10 mm², 6% around 15 mm² and 4% in areas above 20 mm². These results were validated in three conditions: flat base, tilted base and curved base.

Preliminary real tests were carried out with 35 volunteers obtaining a total of 97 wheals, and they showed that the

system is able to find and measure almost all wheals (97% approximately) found by an allergist. The system's outcomes were provided in seconds. The area and diameter measures were very accurate independent of lighting and skin colour factors. However, it also obtained several false positives, which had to be analysed and removed. It seems that some of the false positives could be discarded by a combination of parameters, for example, determining a relationship between the area and height. This would be a statistical process which involves many tests, so future work will focus on carrying out a larger clinical test in order to obtain enough data to apply statistical learning algorithms.

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