

# Measuring Stereoacuity by 3D Technology

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**Abstract.** This paper presents a novel method for measuring with great precision the stereoacuity, that is the smallest depth difference that can be detected in binocular vision. The proposed technique is implemented by a software program that runs on a PC with 3D capabilities. The 3D technology is exploited to provide two different images to the two eyes. The measurement is performed by a classical random dot test, but differently to other tests printed on paper or plastic, the images shown to the patient can vary and the disparity between the two images can be set in order to exactly measure the stereoacuity. Moreover, thanks to the exploited 3D technology, the test does not present any monocular clue. These features allow delivering the test also in groups (instead of individuals) like school classes, and to reduce the risk of undetected amblyopia. The system can be easily operated also by not specialized personnel and this may further increase the cost efficiency of the test. We present the experiments carried on with a large set of children of age between five and seven years. We discuss the results and compare our technique with some traditional approaches.

**Keywords:** Stereopsis · Randomdot test · Amblyopia · 3D

## 1 Introduction

*Amblyopia*, otherwise known as ‘lazy eye’, is reduced visual acuity that results in poor or indistinct vision in one eye that is otherwise physically normal. It may exist even in the absence of any detectable organic disease. Amblyopia is generally associated with a squint or unequal lenses in the prescription spectacles. This low vision is not correctable (or only partially) by glasses or contact lenses. Amblyopia is caused by media opacity, strabismus, anisometropia, and significant refractive errors, such as high astigmatism, hyperopia, or myopia. This condition affects 2–3% of the population, which equates to conservatively around 10 million people under the age of 8 years worldwide [17]. Children who are not successfully treated when still young (generally before the age of 7) will become amblyotic adults. As amblyotic adults, they will have a normal life, with no proven losses in terms of education and occupation opportunities [5], except that they are prohibited from some occupations and they are exposed to a higher risk of becoming seriously visually impaired. The best described long term consequence of amblyopia is an increased risk of bilateral blindness, caused most

frequently by traumatic eye injury in younger people and age related macular degeneration in older people. The projected lifetime risk of vision loss for an individual with amblyopia is estimated around at least 1–2% [13].

For these reasons screening for amblyopia in early childhood is done in many countries to ensure that affected children are detected and treated within the critical period, and achieve a level of vision in their amblyopic eye that would be useful should they lose vision in their non-amblyopic eye later in life. However, there is no strong scientific evidence that preschool vision screening is cost-effective and some researchers suggest that health authorities should stop purchasing pre-school vision screening services [14].

One factor that weakens the effectiveness of amblyopia screening is that population-based screen tests can suffer from a very low sensitivity and specificity. Several methods are available for the measurement of stereopsis. The most common procedures are anaglyph (with use of red-green filters) and vectographic (with use of polarized filters) procedures. However, these tests since they have monocular clues [12] and may result difficult to pass even for normal people can have low sensitivity and specificity. In one proven case, screening for amblyopia by the local nurses using the visual acuity tests or random dot stereopsis test alone displayed a very low sensitivity (around 20 %) [4].

In this research work, we extend the approach of [11] and we present our research project that has the main goal of developing a method (called 3DSAT) for measuring with precision the stereoacuity of a patient with the main goal of avoiding the typical weaknesses of classical stereo tests. 3DSAT aims to be:

- Very **easy to deliver** at a **low cost**. Even unqualified personnel can perform the test, thus increasing the widespread use and reducing the cost of the test.
- With a very high **sensitivity** (also called the true positive rate, or the recall rate in some fields): its measure of the proportion of actual amblyopic positives which are correctly identified as such is equal to 100 %. In this way it reduces the risk of undetected amblyopia.
- With an acceptable **specificity** (sometimes called the true negative rate): its measure of the proportion of negatives which are correctly identified as such is near to 100 %. This has the goal of avoiding frequent visits with more qualified (and costly) personnel.

3DSAT exploits a 3D computer system, a modern technology able to reproduce stereo images on computer screens. There are already some works on using 3D monitor for stereotest and for amblyopia treatment [15]. Our method advances w.r.t. [7] because it implements Random dot instead of Wirt tests, and extends the work presented in [3] with more advances features (like use of active 3D glasses, use of multiple images instead of simple random dot circles).

In this paper, first we describe stereo acuity and its evaluation using random dot test through the development of an application exploiting the 3D technology. Then, we show the test procedure defined to execute the tests on a set of children using this application. Finally, we show and analyze the results of this experiment by highlighting pros and cons of our research work.

## 2 Related Work

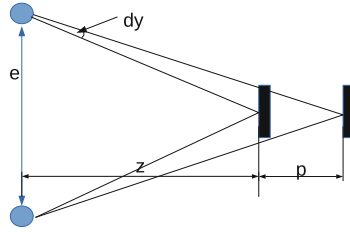
In the last two decades, many researchers have developed different systems exploiting 3D technology to recreate virtual environments that can be very useful for traditional processes in different fields, such as industrial field and healthcare. In last years, many computer devices have been designed in order to create the emulation of five senses using classic computers. The emulation of eyesight is based on the use of digital shutter glasses which allow recreating depth sense by seeing the 2D screen of computer [2, 6, 16]. After different studies about this technology, some projects started to develop applications replicating medical work flows to treat eyes diseases, such as amblyopia and stereopsis deficiency. Among these applications, there are systems that only use typical technology in order to make available your solution at patients and medical personnel [15]. These applications can be subdivided in two categories. The first one is formed by applications that can permit to substitute traditional processes (e.g., occlusion for amblyopia treatment) with innovative techniques that are able to apply particular occlusion digital filters exploiting existent videos and video games [1]. In this way, young patients can do treatment with funny and peaceful approach [8]. Second category is formed by applications emulating traditional process made by oculists to make some measurements, such as stereoacuity and stereopsis [7, 9, 18]. The quality of stereopsis can be tested using the Lang stereotest. It consists in a random-dot stereogram on which a series of parallel strips of cylindrical lenses are imprinted in several shapes, which separate the views seen by each eye in these areas. Without stereopsis, the image seems only a field of random dots, but the shapes become detectable with increasing stereopsis, and generally consists in several simple shapes, such as a cat, a star as well as a car. This last feature facilitates the use of Lang test in young children. In the next section, we present how the stereo acuity test can be emulated using standard technology and our research work will be introduced in order to understand different technical aspects about software development.

## 3 3DSAT: A 3D Stereo Acuity Test

### 3.1 Stereoscopic Acuity and Its Measurement

Having two eyes, as being humans and animals, located at different lateral positions on the head permits binocular vision. It allows seeing two different images that are used to provide a means of depth perception. Through complex brain processing, the human brain uses the binocular vision to allow some important features of sight, such as binocular disparity, discrimination of object size, and surface orientation to determine depth in the field of view. This particular brain skill is defined as *stereopsis*.

Stereopsis is tridimensional vision that is defined by simultaneous stimulation of retinal points that are horizontally disparate. The depth perception doesn't only depend by binocular vision, but it is also defined by different elaborations of mind, perceptive sensations and physiological phenomena whose knowledge



**Fig. 1.** Mathematical model for stereo acuity.

allows to recreate the sensation of distance and depth. The sense of stereopsis is acquired between the first three or four months of life by being humans.

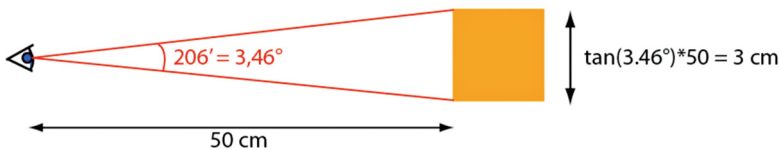
The total or partial stereopsis absence is cause of some pathologies, such as blindness on one eye and strabismus. The examination of stereopsis ability can be evaluated by measuring stereoscopic acuity.

Stereoscopic acuity, also named stereoacuity, is the smallest measurable depth difference that can be observed by someone with two eyes and normal brain functions. It had been invented by Howard and Dolman who explained stereoacuity with a mathematical model as follows in Fig. 1. The observer sees a black column at a distance  $z$  of 6 m (=20 ft). A second columns, that is behind it, can be translated back and forth until it is just detectably nearer than the fixed one. Stereoacuity is the distance between the two positions, converted into an angle of binocular disparity. Equation 1 shows how to convert the depth  $p$  in order to obtain the angle of disparity  $\delta y$  in arc of minutes.

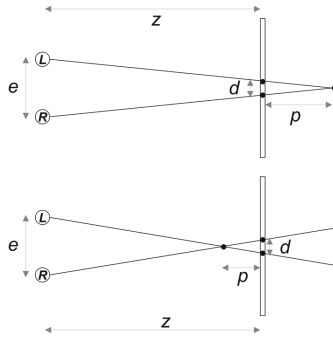
$$\delta y = c e \frac{p}{z^2} \tag{1}$$

In Eq. 1,  $e$  is the interocular distance of the watcher and  $z$  the space of the fixed column from the eye. To transfer  $\delta y$  into the unit of minutes of arc, a multiplicative constant  $c$  is inserted whose value is 3437.75 (1 rad in arcminutes). The ‘arc of minute’ unit permits to evaluate dimension of an object in degrees of angles (Fig. 2). This approach is very useful because it is possible manage perceived dimensions of objects according to distance of observer from the same objects.

The stereoacuity of being humans is excellent when its value is between 15 and 30 seconds of arc.



**Fig. 2.** Calculation of arcseconds



**Fig. 3.** Application of geometrical model using stereoscopic screen. In this image, the model only considers the middle line of screen.

At present, there are different procedures to measure stereoacuity without using cumbersome two-peg device. The difference between screening for the presence of stereopsis and a measurement of stereoacuity is very important. To establish that depth can be seen in a binocular views, a test must be easily managed and not subject to misunderstanding. These tests can measure stereoacuity using either real stereogram or the emulation of stereogram using 3D technology. Furthermore, there are different factor that must to be avoided in order to measure the correct value of stereoacuity:

- Low contrast.
- Brief duration exposures (less than 500 milliseconds).
- Pattern elements with small space between them.
- Errors due to uncorrected or unequally corrected refraction (monovision).

In order to get a good measurement of stereopsis by avoiding the described problems, the Random-dot stereogram (RDS) is widely used because it permits to obtain a test procedure, named Randot stereotest, that is easily administrated and not subject to deception. RDS consists in a stereo pair of random-dot images viewed either with the aid of a stereoscope or the eyes focused on a point in front of or behind the images. In this way, the RDS system produces a sensation of depth, with objects appearing to be in front of or behind the display level. Randot stereotest has been easily emulated using 3D technology in this research work, i.e. a 3D based software, named 3DSAT, has been developed by exploiting IT potentiality. In particular, the random small pattern elements are the pixels of PC screen forming digital images, one behind the other, showed to the patient using 3D glasses. Therefore, formula 1 has been adapted by substituting pegs with pixels and the geometrical models has been redefined according to the use of PC.

Figure 3 shows how to apply Howard and Dolman model using a 3D display. The observer's eyes, which are indicated with  $L$  (left) and  $R$  (right), have a binocular distance defined by  $e$  and they are away from screen plane with

distance  $z$ . The value  $d$  is defined as pixels disparity between two stereoscopic images that are shown on stereo screen.

The disparity of a couple of stereo images, defined as  $x_l$  and  $x_r$ , is simply the difference along x-axis of screen that is measured in pixels.

$$d = x_r - x_l \quad (2)$$

Therefore, the geometric model of perceived depth is defined in following way (assuming that  $p$  is small w.r.t.  $z$ ):

$$p = \frac{z \cdot d}{e} \quad (3)$$

In Eq. 3, it is important to highlight depth perception that is directly proportional at observers distance. Thus, a observed stereo image will allow to perceive different depths from different distances. By substituting the depth  $p$  in Eq. 1, we find that the stereo acuity can be computed as:

$$\delta y = c \frac{d}{z} \quad (4)$$

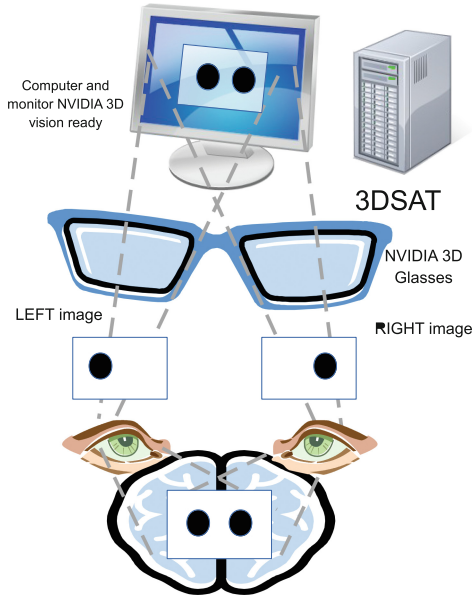
As desired, the Eq. 4 measures the stereo acuity in angles and it does not depend on the interocular distance. In the next subsection, we would introduce the way to apply this geometrical model using 3D technology and we describe the software system to emulate Random Dot test using this technology.

### 3.2 Using 3D for Stereo Acuity Test

3DSAT is a system based on a 3D computer system. The current version is based on the NVIDIA® 3D Vision™ technology, although other 3D technologies may be supported as well in the future. The NVIDIA 3D Vision technology is one of the most accessible 3D technologies available on the market today, it requires a standard personal computer with a NVIDIA graphic card, a monitor 3D Vision ready, which is capable of a refresh rate of 120 Mhz, and a NVIDIA LCD shutter glasses. The NVIDIA 3D vision is based on active shutter technology. With this method, the left and right eye images are presented on alternating frames, but since these monitors are capable of 120 Hz, each eye still sees a full 60 Hz signal that is equivalent to the refresh rate on LCD monitors today. This offers a number of advantages with respect to other stereoscopic technologies like polarized or anaglyphs glasses or head-mounted displays:

- **Full image quality per eye:** In 3D mode, each eye receives the full resolution of the display for the highest possible image quality for text and objects. The colors are not altered and both eyes can receive images of the same quality.
- **Wide viewing angle for 3D:** Because full images are presented on alternating frames, there are no restrictions on the viewing angle in 3D mode. Users are free to move their heads vertically or horizontally within the full viewing angle of the display without losing the 3D effect or suffering increased ghosting which allowing for comfortable viewing for continuous gaming or movie watching.

- **Personalized fit:** The NVIDIA glasses have top-of-the-line optics, include adjustable nose pieces, and are modeled after modern sunglasses. They can be worn over prescription glasses.
- **Acceptable cost:** The cost of the glasses is around 140 USD, while the 3D ready monitors cost a little more than the traditional monitors but they offer a better quality also in 2D.



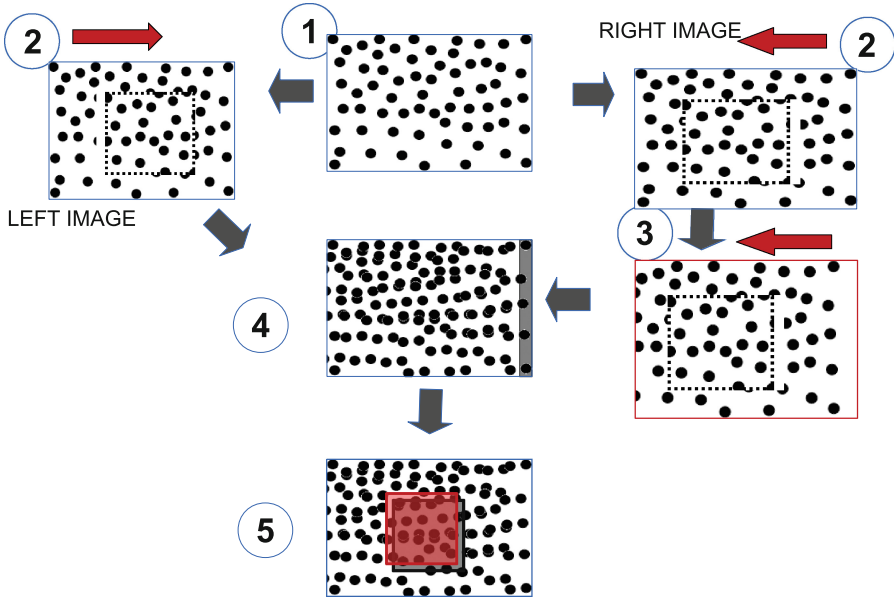
**Fig. 4.** Using 3D to separate the dots

In the context of amblyopia, 3D technology can be used also in the treatment with the goal of complementing the classical therapy of eye patching [10].

### 3.3 3DSAT

The system we have developed for 3DSAT consists in a normal PC desktop connected to a 3D monitor (3D Vision-Ready Display). The PC must be 3D capable and have all the 3DSAT software installed on it. The patient wears the NVIDIA active LCD shutter glasses that allow viewing a different image from the left and right eye. The scenario is depicted in Fig. 4. This principle is the separation of the images provided to the right and left eye.

The stereo image to show to the child is built by the following steps as depicted in Fig. 5.



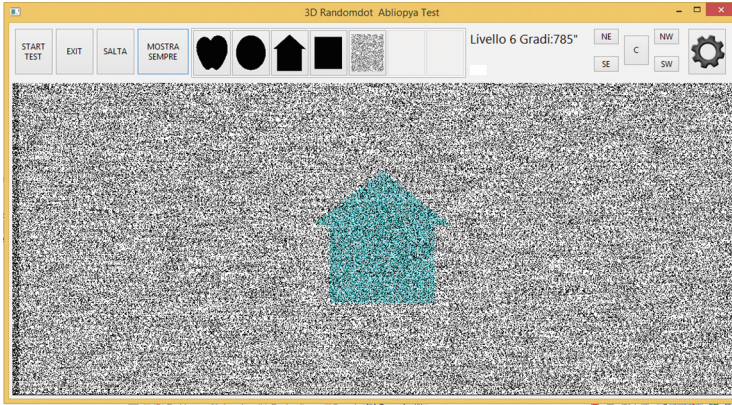
**Fig. 5.** How the 3D image is created

1. A random dot image is created (every time with different distribution of the dots)
2. The pixels corresponding to the shape to be shown (in the Fig. 5 a square) are translated with a desired disparity (in terms of pixels) in two opposite directions for the left and the right image.
3. One of the two images is entirely translated in the same direction.
4. The two images are composed in a unique 3D image shown to the child.
5. The child, in the presence of stereopsis and wearing the 3D glasses, perceives the shape in depth.

The shape is seen in depth because the left eye sees one set of dots and the right eye sees a second set of dots. The dots are identical, except for the dots within the square that have been horizontally displaced in order to try to emulate the distance of interocular disparity. Using this technique, our brain fuses the two 2D retinal images into a single image in which displaced pixels define a shape that is perceived with a different depth. Through identifying corresponding points, ‘matching primitives’ in the slightly offset retinal images of the left and right eye, the images can be aligned in such a way as to reveal depth information. The nasal displacement produces the stereoscopic perception that the square of circles is raised off the screen [19].

The translation of one entire image (step 3) eliminates any clue of the shape one could have without the 3D glasses: if the two images are composed in the same position all the pixels except those translated are in the identical position and are completely overlapped. This would cause an increase in the composed





**Fig. 6.** User interface of 3DSAT application

image of the density of the pixels in correspondence of the shape. Wearing the glasses would eliminate the diversity of density but without the glasses one would have a clue of the shape. By translating one image we restore an equal density of the dots.

### 3.4 Software Development and Use of 3DSAT

The 3DSAT software has been implemented using Java and OpenGL and works under Microsoft Windows systems. A screenshot of the software is shown in Fig. 6. At the beginning the user inserts the patient data, selects an image set<sup>1</sup>, the starting disparity, the distance of the child from the screen, the dimension of the screen and the dimension of the shapes. After a preview of what the shapes will look like (as shown in Fig. 6), the software randomly chooses a shape in the shape set and shows the 3D random dot stereotest for that shape. The child either says or indicates what it sees and if the guess is right then the software chooses another shape and decreases the angle of disparity. The software assesses a certain level of disparity if the child can guess the shapes for that level for three times with maximum one error. The minimum angle of measurement depends on the monitor and on the distance of the child, and some examples are reported in Table 1.

*Policies.* In order to reduce the number of false negative (i.e. amblyopic not correctly identified and falsely passing the test) and increase the test **sensitivity** we have devised the following policies: (i) the shape is randomly chosen every time, (ii) also the control null image (no shape is shown) can be inserted, (iii) either the user that delivers the test has no clue about which shape is currently displayed, (iv) we have checked the absence of any monocular clue by using the

<sup>1</sup> 3DSAT now provides set of images similar to those presented in the LANG stereotest I and II, TNO, LEA, pacman and letters. New image sets can be easily added.

**Table 1.** Minimum angle definition according to dimensions, resolution and distance of the PC screen.

| Dim | Resolution      | Distance | Minimum angle |
|-----|-----------------|----------|---------------|
| 23" | FHD 1920 × 1080 | 40 cm    | 136.8"        |
| 23" | FHD 1920 × 1080 | 80 cm    | 68.4"         |
| 27" | FHD 1920 × 1080 | 40 cm    | 160.5"        |
| 27" | FHD 1920 × 1080 | 120 cm   | 53.5"         |

software both without glasses and with glasses but with one occluded eye. In both cases we were unable to identify the images.

In order to reduce the number of false positives (i.e. non amblyopic falsely failing the test) and increase the test **specificity**, we have devised the following policies: (i) the shape is shown as image: if the child has difficulties to recognize the shape and identify its name, he/she can simply point his/her finger, (ii) the test has initial phase in which no measurement is taken and the images are shown colored: in this way the child understands what the shape will look like when the actual measurement is started and the color disappears, (iii) when a child fails the test, the test can be retried with a different set of images (after the equipment is checked for failures). Since the images are randomly chosen, the test can be repeated without loss of sensitivity (differently from the classical test on paper).

## 4 Experiments

We tested the system on a total population of 90 subjects with age between 5 years and 7 years (Fig. 7). In the group there was a small presence of amblyopic subjects (known before starting the tests). The main aim of the test was to verify the presence of false positives or false negatives results. Due the young age and the high number of the people taking the tests in the same session, we decided to organize the tests as a group game. Indeed, we planned that the aim of the game was to guess a given shape visualized on the screen, wearing the 3D glasses. Obviously, only the child with the glasses would be able to see what happens on the screen, while other children can see just a noisy image. Children were asked to guess the shapes wearing glasses one after the other. It turned out that this modality fits very well in a context of group screening, especially with young and lively children. With the traditional tests, such as Lang test, young patients would suggest each other the correct results, causing false negatives. With our computer-based system, shapes to be guessed change every time, making cheating very difficult. This could highly reduce the number of false negatives cases. Also, our approach permits to show a great number of different shapes (also possibly expandable and customizable), reducing further the number of false negatives caused by wild guesses. However, for the tests we just used shaped derived from LEA, TNO and LANG traditional tests. The



**Fig. 7.** A child is using 3DSAT with LCD shutter glasses.

group screening proved to be time effective: the mean time required to test one person is 2 min, faster than the traditional way. In total we tested 90 subjects for a total of 180 test results. We identified 8 potential positive cases, confirmed by previous medical diagnosis. We clustered test data grouping the distance from the screen and the data is shown in Table 2.

Looking at the collected data, we observe that the minimum and maximum stereo acuity values decrease linearly with the increasing of the distance. The mean values depend on the stereo acuity of the various subjects taking the tests, however they present too a decreasing trend with the distance increase. This is expected since by increasing the distance, the minimum measurable angle of stereopsis decreases (see Table 1).

**Table 2.** Distance from the screen, mean, minimum and maximum stereo acuity values.

| Distance | Mean     | Min      | Max      |
|----------|----------|----------|----------|
| 40 cm    | 398.12'' | 139.12'' | 962.02'' |
| 50 cm    | 407.44'' | 128.27'' | 769.62'' |
| 60 cm    | 278.84'' | 106.89'' | 641.35'' |
| 80 cm    | 170.41'' | 79.49''  | 481.01'' |
| 100 cm   | 231.12'' | 64.13''  | 384.81'' |
| 120 cm   | 109.32'' | 53.44''  | 213.78'' |
| 150 cm   | 101.06'' | 42.75''  | 299.29'' |
| 160 cm   | 100.21'' | 40.08''  | 240.50'' |
| 200 cm   | 51.30''  | 25.65''  | 64.13''  |

## 5 Conclusions

We have presented an application that emulates random-dot test using 3D technology. 3DSAT has been used for our experiment on young children and early results have been considered promising. The test procedure has demonstrated the potentialities of our application compared to the traditional approach. Therefore, our research work proposes an innovative and better approach for this test, which is also frequently used for detecting amblyopia, strabismus and suppression, and to measure stereoacuity. Furthermore, we have wanted to demonstrate that is possible to get innovative solution in healthcare exploiting low cost technology and free software. Thanks to this approach, 3DSAT may be added into a bigger IT system that allows sharing patient information using web and mobile technology in easy way. About this issue, new developments have been planned in order to try the real potentiality according to needs of both physicians and patients who can use this technology in the future.

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