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Depth separation in ten observers with a new stereoscopic X-ray acquisition system

Th. Moll[1], F. Turjman[1], C. Picard[2] J. P. Bres[1], M. Amiel[1]

[1] Creatis UMR CNRS 5515, Hôpital L. Pradel, 69, Bd Pinel, F-69 003 Lyon, France
[2] General Electric Medical System Europe, F-78 530 Buc, France

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Abstract. The aim of this work was to assess the depth separation of a new X-ray digital stereo angiographic system through visualization on a stereoscopic monitor. Before starting the clinical trial of this new stereo–digital angiographic system, it seemed to us mandatory to assess the inherent performance of the system to depict depth information, as well as the ability of the users to work with it. With this idea we designed a global test based on the observation of a physical test object by the potential users of the system, during a session long enough to simulate an angiographic study. The acquisition system consisted of a twin focal-spot X-ray tube and a standard DSA DG 300 (General Electric/CGR). The stereo display was controlled by a liquid crystal modulator placed in front of a black-and-white monitor. Special polarized glasses worn by the observers allowed right- and left-image separation. Depth separation was measured in ten observers by means of a stereoscopic test object. Six of the ten observers were able to locate accurately three-dimensional patterns separated by a 12- to 1.5-mm gap. No learning effect was noticed. This result suggested that stereo display through wireless polarized glasses coupled to up-to-date digital subtraction angiography technology may provide an accurate and ergonomic way to a dimensional enhancement of X-ray angiography.

Key words: Digital subtraction angiography – Image display – Stereoscopy

Introduction

Stereoscopic angiography provides a useful and efficient means of overcoming the problem of depth separation and object overlapping on a single projection of a three-dimensional object [1–6]. Several studies have pointed out the great advantage of this technique in clinical condition, as vascular neighboring of a lesion can be three dimensionally assessed and vessels overlapping discriminated [7–15]. It has also been demonstrated that detail visibility is improved from the fact that the signal-to-noise ratio is increased by a factor $\sqrt{2}$ by a twin exposure of the same object [10–17]. Despite these advantages, stereoscopic X-ray technique is still experimental, probably because of practical considerations. Technology of twin focal X-ray tubes has solved inherent difficulties at the acquisition step of the radiological process, but displaying stereoscopic images still remains difficult as stereoscopes based on optics and mirrors are used. Recently, stereoscopic video monitors using polarized shutters and glasses has been commercially available. This technique is expected to provide an ergonomic display device allowing free-hand viewing of dynamic scenes and simultaneous observation by several observers [18].

The aim of this study was to assess, in terms of depth detectability, the performance of a new stereoscopic angiographic system equipped with such a stereoscopic video monitor.

Materials and methods

The X-ray tube was a twin-focus angiographic tube. Focus size was 0.8 × 1 mm for both foci. Interfocal distance was 65 mm. The light amplifier was a triple-field model with selectable field size of 160, 230, or 320 mm. With a 230-mm field size and 512 × 512 matrix, the pixel size was 450 µm.

A digital subtraction angiography (DSA) system (DG 300 General Electric/CGR) was used for image acquisition, digitization, and monoscopic display. Stereoscopic display was obtained by using a liquid crystal stereoscopic modulator (TEKTRONIX, Les Ulis, France) placed in front of a black and white 1190 × 960 video monitor with a 100-Hz frame rate, with special polarizing glasses worn by the user providing the right- and

Correspondence to: M. Amiel

left-eye views. As the frame rate is 50 Hz for each eye, the display does not present any flicker and is thus comfortable.

Offset of right and left images was adjustable thanks to a command acting on the video sweep of the camera. This allowed compensation of the excessive stereo shift due to the magnification factor and kept stereo display comfortable.

Method for measuring the observer depth separation

The ability of the observers to perceive depth information was assessed by the method of the plus signs described by Doi [4]. The principle of this method is to ask the observer to predict, on the stereoscopic image of a plus sign made of two thin wires of metal separated by a gap, whether the horizontal branch of a plus sign is above or beneath the vertical branch. The gap between the two branches may be adjusted to make the test more or less sensitive.

Therefore, a plus sign phantom (Fig. 1) was constructed with two complementary layers in methacrylate allowing arrangement of eight rows and eigth columns of plus sign made with 0.9 mm in diameter and 10-mm-long copper wires. From rows 1–8, the gap between branches ranged from 1.5 to 12.0 mm. On each row the configuration of the sign was randomly determined.

Applying the radiographic technique to this phantom with a quarter of turn in anterior and posterior projection gave eight stereoscopic images of 64 plus signs, thus 512 plus signs to read. Exposure conditions were set at 50 kV, 40 mAs, one image per second, and magnification factor equal to 1.12 (focal spot to detector distance = 960 mm, object to detector distance = 100 mm). The field of view of the light amplifier was 230 mm.

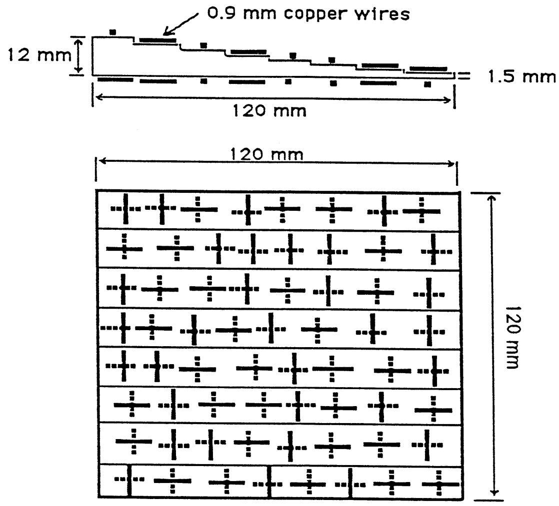

Fig. 1. Plus phantom used for the determination of depth separation. *Top* profile view; *bottom* front view

Table 1. Experience of the observers and compliance with the protocol

No.	Specialty	Experience in X-ray stereoscopy	No. of images read	Duration of the session (mn)
1	Physicist	None	8	24
2	Radiologist	Trained	8	43
3	Radiologist	None	8	40
4	Cardiologist	Trained	8	35
5	Radiologist	None	5	22
6	Radiologist	Trained	8	36
7	Radiologist	None	8	30
8	Radiologist	None	8	28
9	Radiologist	None	8	27
10	X-ray technician	Trained	8	33

Reading protocol

Seven radiologists, one cardiologist trained to cardiac X-ray procedures, one physicist, and one X-ray technician were involved in the reading protocol (Table 1). For each plus sign, they were asked to predict which branch (horizontal or vertical) was in the anterior plan. The order of the eight images was randomly assigned so that thick or thin rows were presented in random order. As a result, the rate of correct answer was computed according to three factors: depth separation, distance from the center of the field of view, and time elapsed from the beginning of the reading session.

Analysis of RCA

Ability of the readers to perceive depth information was assessed by the rate of correct answer (RCA) for each gap. As RCA is statistically related to the probalility p of each plus sign to be correctly read, we tested this probability to be superior to 0.5 as a proof of depth perception. Assuming that RCA is a binomial variable (sum of 64 random variables per gap that may be equal to 0 or 1) [19], the null hypothesis $p = 0.5$ (in other words, reader gives a random response) may be rejected if RCA is superior to 0.61 with a first-type error 0.05 and a second-type error smaller than 0.01.

Results

Compliance with the protocol

Nine of the ten observers completed the reading session. The last one declined to continue after having read five images (320 plus signs), alleging ocular fatigue. The duration of the session is tabulated in Table 1.

Depth separation

Rates of correct answer according to depth separation for each reader are shown in Table 2. With respect to the statistical analysis mentioned above, six of the ten readers (nos. 2–4, 6, 8) perceived depth information from 12.0 to 1.5 mm. For three readers (nos. 5, 9, 10),

Table 2. Rate of correct answers according to gap distance separating the branches of the plus signs

Observer	1	2	3	4	5	6	7	8	9	10
Thickness (mm)										
1.5	0.422	0.813	0.859	0.906	0.650	0.828	01.00	0.703	0.500	0.594
3	0.500	0.891	0.938	0.984	0.525	0.906	01.00	0.906	0.719	0.531
4.5	0.406	0.875	0.875	0.984	0.450	0.891	0.969	0.953	0.406	0.688
6	0.391	0.922	0.984	0.984	0.525	0.844	0.984	0.891	0.578	0.524
7.5	0.563	0.969	0.984	0.953	0.525	0.875	0.969	0.922	0.500	0.609
9	0.469	0.875	0.984	0.984	0.475	0.859	0.922	0.891	0.563	0.540
10.5	0.500	0.906	0.969	0.969	0.650	0.906	0.969	0.859	0.688	0.484
12	0.563	0.922	0.952	0.953	0.525	0.844	0.953	0.750	0.547	0.641

NOTE: According to Table 1, the number of plus signs read is 64 for all observers except no. 5 (only 40)

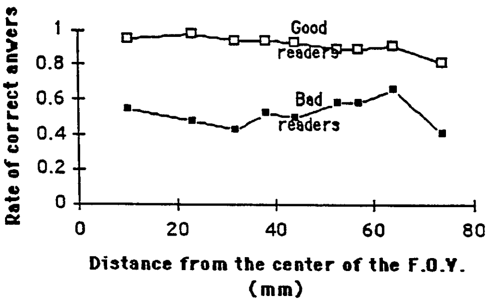

Fig. 2. Mean of correct answer over good and bad stereo readers of rate according to the distance of the plus sign from the center of the field of view *(F.O.V.)*

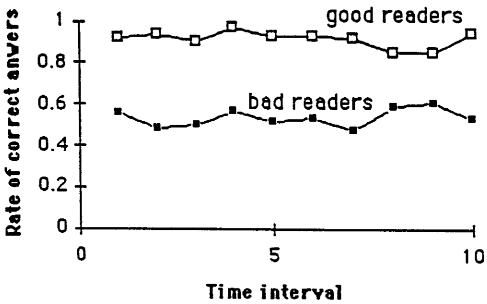

Fig. 3. Mean of correct answer over good and bad stereo readers of rate according to the time interval during which the reading was done

who demonstrated a poor ability to depth perception, RCA fluctuated below and above the 0.61 threshold. One reader (no. 1) did not perceive depth at all. As a result, this indicates clearly that depth resolution of this apparatus is at least equal to 1.5 mm.

Effect of the distance from the center of the field of view

In Fig. 2 the mean of RCA over good and bad stereo readers is plotted against the distance of the plus sign from the center of the field of view. Although no statistical analysis was done, a slight trend toward decrease in RCA is observed in good stereo readers when the plus sign is located at the periphery of the field of view.

Time effect

In order to study the effect of ocular fatigue on stereoscopic acuity, the duration of the reading session of each observer was recorded and divided into ten equal intervals. Then the mean over good and bad stereo readers of RCA was reported, according to the time interval during which the reading was done (Fig. 3). No obvious difference in RCA was observed along the ten successive time intervals of the ten readers.

Discussion

In terms of depth separation and proportion of good stereo observers, our results are similar to those obtained by Doi [4] and Takahashi et al. [5]. In the conditions of our experiment, depth resolution of the system is at least equal to 1.5 mm. This depth resolution is far sufficient in most of the clinical situations, where relatively small vessels (2–5 mm in diameter) are to be imaged and spacially located. In some particular cases, such as stereotactic steering of fine needles, a higher resolution would be required. We have considered this aspect out of this study because it assumes that the observer should be able to depict a stereo shift smaller than one pixel size with a matrix size of 512 × 512. In fact, as a punctiform object appears bigger than in reality because of the shape of the "punct spread function," the above assumption could be tested in a fitted experiment.

Like Doi [4] we did not notice any learning effect as depicted by the constancy of the RCA along the experiment. Although the size of our sample of observers is small, we did not find any difference from observers who had not yet used the apparatus from those who had used it for catheterization in dogs.

It is interesting to note degradation of performance in stereo vision at the periphery of the field of view. In fact, this slight trend suggests that differences in stereo vision from conic projection with natural human vision are not to be neglected. However, depth separation at the periphery of the field of view remained excellent for good stereo readers.

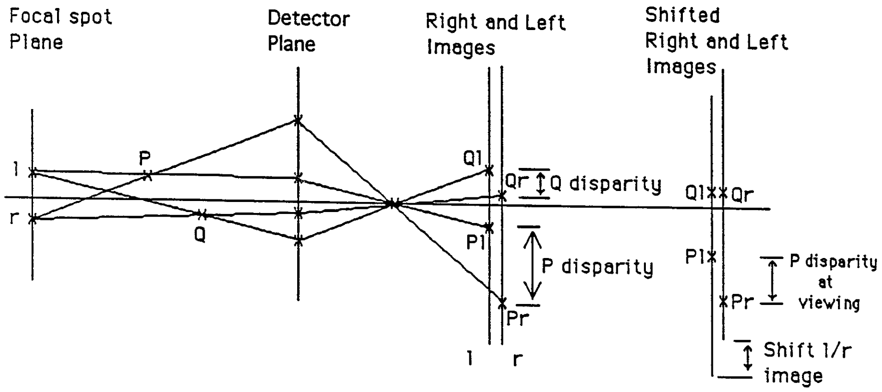

Fig. 4. Stereoscopic disparity between left and right images of a punctual object is related to the geometric magnification of the plane to which it belongs. To keep the stereoscopic disparity in comfortable display value, left and right images may be shifted. Then the stereoscopic disparity remains in comfortable viewing value for all the depth of the three-dimensional scene

In this experiment, the effect of reminiscence of the different components of the system was avoided by the fact that a low acquisition rate was used (1 s elapsed between right and left image). Previous studies [1, 12, 14] have shown that an efficient stereo effect for angiograms is obtained with usual image rate (two images per second) at which reminiscence of the different components of the system may be neglected.

Two particular aspects make this system different from those previously assessed by objective depth resolution measurements. Firstly, it was now possible to tune the stereo shift between right and left images. Binocular disparity must be kept in narrow limits so as to deliver a comfortable binocular vision [19, 20]. From the point of view of the observer, angular disparity results from two factors: viewing distance and stereo shift on the display screen. Viewing distance must be freely chosen by the observer with regard to practical conditions in a clinical X-ray room and personal habits. Stereo shift is determined by a combination of several factors (Fig. 4). Interfocal distance is built-in, determined by the stereo X-ray tube and set to 65 mm so as to fit with conventional angiography where object-to-film distance is usually kept constant and smaller than in digital angiography. Magnification due to electronic magnification of the light amplifier must be interchangeable so as to allow several fields of view and spatial resolution. Geometric magnification, on the contrary, with this previous factor cannot be easily controlled and changes during the examination of the same patient from one projection to the other. Therefore, it appears advantageous for the radiologist to be able to control one of these factors. In this apparatus, lateral shift of right and left images was done by acting on the sweep of the video camera. This tuning is performed before angiographic acquisition, when the operator adjusts the positioning of the patient with stereofluoroscopy. When all geometric parameters are set, the operator tunes the shift of the video camera in order to obtain an optimal stereo shift providing a comfortable and efficient stereo display. Of course, this setup was no longer changeable after the acquisition of the stereoangiography.

Secondly, we used a liquid crystal modulator coupled to wireless circular polarized glasses. Two questions were to be assessed: Firstly, it was necessary to assess if light attenuation due to this device would not impair the radiological images. Although the brightness of the monitor appeared inferior to those to which radiologists are accustomed, image quality was judged as excellent by all observers. Wearing polarized glasses did not appear to be a limitation in clinical use. The second question concerned whether the non-perfect extinction during one eye turn-off time could allow stereoscopic visualization free of phantom image on highly contrasted images such as those used in radiology [18]. In this experiment no artifact of this type was noticed and excellent depth resolution was obtained.

In conclusion, this experiment demonstrates that liquid crystal modulator and polarized glasses, coupled to classical DSA architecture, is able to provide an accurate means to add three-dimensional information to radiographic projections. In addition, the absence of any wire connecting the passive polarized glasses to the active modulator suits this technology for applications such a stereofluoroscopy.

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Book review

European Radiology

Polk, C., Postow, E. (eds.): Handbook of Biological Effects of Electromagnetic Fields, 2nd edn. Boca Raton: CRC Press 1996. 618 pp., (ISBN 0-8493-0641-8), £ 99.00.

Since publication of the first edition of this book in 1986, many new research reports on the biological effects of electric and magnetic fields have appeared, such as the effects of static and extremely low frequency (ELF) magnetic fields, and the effects of non-modulated microwave fields; also, new numerical methods for field computation have been introduced. The Appendix on Safety Standards has been thoroughly updated to include the many new standards issued by different agencies to insure the protection of individuals exposed to electromagnetic (EM) fields. Some topics dealing with the biological effects of electric and magnetic fields are controversial, in particular the potential health effects of very low intensity, non-thermal fields (Chap. 11). In reviewing the vast amount of experimental data which have been obtained in recent years, the authors tried above all to present known science and to differentiate between what is clearly established, what is suggested by available evidence without being convincingly proven, and what is conjecture at the present time, although some controversial topics are treated by different contributors from different points of view.

The introduction to this handbook is written by one of the Editors and treats two topics: (i) the evaluation, based on theoretical background, of how much of the EM energy present in the environment can penetrate the organism and (ii) the difference between 'ionizing' and 'nonionizing' radiation. This excellent introduction puts in the proper perspective the different behavior and penetration properties of (DC) fields that do not vary in time and of fields, which do not involve radiation at all, and the more rapidly varying radiofrequency (RF) fields, with frequencies around 10 MHz and higher, which require proper application of the theory of electromagnetism to study their effects in biological tissues.

Part I of the book treats in some detail the theoretical and experimental aspects of the dielectric properties of biological materials required for a quantitative discussion of the interaction of electric and magnetic fields with living tissue. The chapter reviews the basic concepts of dielectric phenomena and summarizes the most important dielectric relaxation mechanisms in tissues. The dielectric properties (permittivity, conductivity) of several tissues (blood, muscle, bone, adipose, tumorous, in vivo as well as in vitro) from very low frequency through microwave ranges are reviewed. A section examines the effects of cellular structure on the dielectric properties of tissues and the coupling between the external EM field and the intracellular compartments, including membranes. Finally, the dielectric relaxation properties of tissue water and their relation to other transport properties of biological systems are discussed.

Part II is concerned with the effects of DC and low-frequency fields which do not involve radiation. Chapter 2 deals with the interaction of DC and ELF electrical fields with biological materials and systems. It starts with the study of forces acting on charged particles in fluids and proceeds with the effects of electric fields on membranes and on currents through membranes. This is followed by a discussion of thermal effects of current flow due to electric fields and of the general level of fields, currents and temperatures where biological effects are expected. The next section contains data on the levels of naturally occurring and man-made fields, including electrical signals and noise levels in the body, and on current safety standards. The final section introduces the relationship of electrical fields to tissue growth and applications to therapy.

Chapter 3 is limited to the biological effects of static (DC) magnetic fields. An especially important area of growing interest concerns the biological effects and safety aspects of nuclear magnetic resonance imaging and spectroscopy. This is part of the first section which also reviews other applications of magnetism in physiology and clinical medicine such as magnetic targeting and modulation of drug delivery, magnetic separation of biological materials and noninvasive measurement of blood flow. A large topic area involves mutagenic, mitogenic, metabolic, morphological and developmental effects as well as behavioral effects (on orientation, migration and homing) due to exposure of organisms or biological materials to magnetic fields. The companion Chap. 4 reviews the interaction of ELF magnetic fields with living systems. The possible relationship between exposure to ELF (including 50/60 Hz) magnetic fields from power lines, electrical appliances, machinery and an elevated risk of adverse health effects has become a subject of considerable public interest and concern. The chapter presents a summary of recent experimental research on the biological effects at the molecular, cellular, tissue and animal levels, including effects on reproduction and development, and on cancer cell development. Most relevant are the human health studies, of which a brief summary and critique is presented that concludes that the overall set of information obtained to date from epidemiological studies has not demonstrated a strong association between cancer risk, nor adverse pregnancy outcomes, and residential exposure to ELF fields (see also Chap. 7). Chapter 5 briefly discusses the use of electric and magnetic fields for bone and soft tissue repair and nerve regeneration. The application of short-duration high-intensity electric field pulses which result in electroporation is the subject of the next chapter. Electroporation that short-circuits barriers such as membranes by creating aqueous pathways across lipid-containing barriers, has becomes important not only for the understanding of electric injury but also for local drug delivery to tissue and as a tool in biotechnology for transferring genetic material between different cells. Chapter 7 presents an extensive description and evaluation of the numerous epidemiological studies (residential and occupational) suggesting possibly adverse health effects of power-frequency fields at ELF. Exposure characterization is the most problematic issue in epidemiology. For childhood leukemia, several studies have provided evidence of elevated risk among children living close to power lines. For childhood brain tumors and adult cancers data are not consistent. The weight of evidence also supports an association of putative occupational EMF exposure and increased risk of leukemia and brain tumors. The hypothesis that prolonged magnetic field exposures might increase the risk of cancer in humans deserves continued serious scrutiny. The evidence for reproductive effects is contradictory and lacks consistency.

Part III deals with EM energy which mostly enters living tissue in the form of radiated EM waves. Chapter 8 on experimental radio and microwave dosimetry discusses the measurement methods and techniques of electromagnetic fields outside biological tissues, and in particular the specific absorption rate (SAR), a widely adopted measure of energy absorbed by a tissue. Thermal measurements to determine the SAR are discussed. The related Chapter 9 on computational methods for predicting field intensity presents an account of the distribution of electromagnetic fields in biological media and of the techniques, analytical and numerical (moments, finite elements, finite difference) that are employed to analyze the propagation and absorption characteristics of electromagnetic energy in tissue structures (planar and spheroid models, and complex constructions to represent the human body). Thermoregulation in the presence of microwave fields is the subject of the next chapter, which reviews the limits of human heat tolerance to RF radiation as a function of temperature, vapor pressure and clothing, during normal activity, exercise and in febrile states and analyses, in particular thermal sensation and thermoregulatory behavior aroused by microwaves. Attention is paid to intense or prolonged exposure and to drug-microwave interaction. Chapter 11 is a major chapter on the experimental results concerning the interaction of nonmodulated and pulse-modulated RF fields with living matter. The great interest in this field results from scientific curiosity and public health considerations. The concerns over non-reproducibility of results and non-robustness of effects in biomagnetism studies and the vagaries and pitfalls in the literature are discussed. The chapter presents a systematic account of the results in cellular and molecular biology, in reproduction, growth and behavior, in the nervous system, and continues with a review of the behavioral, neuroendocrine, cardiovascular, auditory and ocular effects, as well as of the effects on hematopoiesis, hematology and on the immune response. The chapter closes with an exhaustive list of references. Chapter 12 is on modulated fields and ‘window’ effects. The condition in which a specific result is found only when the independent variable is within certain well-characterized narrow ranges of values is described as a ‘window’ effect. Both frequency and field strength ‘windows’ have been reported in the bioelectromagnetics literature. Their location is of utmost importance for the elaboration of reliable safety standards. Most of the reported window effects have been observed in the millimeter-wave and the ELF region. Effects of the latter on the auditory system, the brain and the nervous system are reviewed. Finally attention is paid to effects specific to pulsed RF radiation.

The different parts of the book are relatively independent of each other, so they can be consulted directly by the reader whose interest is restricted to a particular, specialized topic. As with the other handbooks of this publisher, each chapter contains numerous tables and graphs which summarize the reviews for the reader in search of factual data.

Prerequisites for a thorough understanding of the fundamentals underlying the biological effects discussed in the book are a good intermediate-level undergraduate course in electricity and magnetism and at least an introductory course in Biology. The reader – either medical physicist, electrical engineer, biologist or medical doctor – should find this book extremely useful as a introduction to each of the topics treated as various chapters, as a rather exhaustive review of recent research or as a guide to the specialized litterature.

P. Van Hecke, Leuven