Review

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History of ultrasound in obstetrics and gynaecology from 1971 to 2021 on occasion of the 50 years anniversary of EFSUMB

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Abstract

Diagnostic ultrasound in obstetrics and gynaecology has experienced a fantastic evolution during the past seven decades. Initial steps with A-mode technology were followed by B-mode and B-mode real-time imaging, then by Doppler and colour Doppler ultrasound, and finally by 3D/4D ultrasound. Other evolutionary steps were the development of high-resolution transabdominal and transvaginal transducers providing high quality images in the first, second and third trimesters of pregnancy, as well as in gynaecology and breast imaging.

The progression from two-dimensional (2D) to three-dimensional ultrasound (3D) and 3D real-time imaging (4D) has brought new options in displaying anatomical structures. In comparison with CT or MRI, it is not a static but functional technique, cheap and safe, and applicable at any time.

Keywords: history; EFSUMB; ultrasound

Introduction

The history of the European Federation of Societies in Ultrasound in Medicine and Biology (EFSUMB) is closely related to the general history of ultrasound [1,2].

Over 65 years of clinical ultrasound (US) in Obstetrics and Gynaecology there have been huge developments in both technical and clinical aspects. Many pioneers, engineers and clinicians in several countries have contributed to this development. In one short article it is not possible to provide a comprehensive description of the changes, so this paper will only focus on some highlights of European US during this time period. It will also cover only the beginning of breast US. For a detailed overview of world-wide US history in Obstetrics and Gynaecology see Woo et al [3] and Levi et al [4].

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First pioneers

As early as May 1951, the surgeon John J. Wild, who had emigrated from Great Britain to Minneapolis in the United States, published the first results of A-mode tissue differentiation on nodes of the female breast in the Lancet using equipment based on military radio frequency technology from the Second World War. The U.S. Navy base at Minneapolis used a 15 MHz ultrasonic transducer installed in a water tank in Pilot training to simulate flight radar over a geographic model of a target region. This took advantage of the $2x10^5$ factor of difference between the speed of radio waves and the propagation of sound in water. Anecdotally, it is reported that Wild secretly gained access to this base with the help of a patient and was inspired there to construct a hand-held US transmitter and detector [5]. Echo signals had been used to simulate enemy terrain for pilot radar training. Based on this 15 Megacycles/second (15 MHz) technol-

ogy, the first clinically applicable linear US scanner was developed in collaboration with the electrical engineer John M. Reid in Minneapolis [6-8]. In 1952, Wild and Reid published 21 cases of A-Mode imaging of female breast tumors with pulsed US waves in comparison to healthy (contralateral or surrounding) breast tissue. They compared this A-mode technique for tissue characterization with needle biopsy. The hand-held US contact-probe used by Wild and Reid consisted of a chamber filled with water, one end of which containing the 0.2 mm thin piezoelectric quartz crystal with a working surface of 9 mm and the other end sealed at a distance of 2 cm with a rubber membrane made of a condom. This "Ultrasonoscope" was handled analogously to a stethoscope, with the wetted rubber membrane placed on the skin. Using a pivoting crystal, driven by an electric motor and worm screw drive, they were able to sweep the US beam by 45 degrees through the skin and the underlying tissue. In that way, Wild and Reid were able to produce and publish a 2D cross-sectional A-mode image of a female breast tumor for the first time [9,10]. In 1952 they also predicted that 3-dimensional (3D) echograms could be generated using this technology [9]. In May 1953, they showed the first real-time image of a 7 mm small tumor of the female breast nipple and reported on differentiation between cystic and solid breast lesions [11]. In 1956, Wild and Reid had examined 117 pathologic findings of the female breast and demonstrated that, when superficial, even small breast tumors could be visualized with these high-frequency transducers [3,12]. Wild and Reid are also regarded inventors of the first A-Mode intravaginal sector scanner and of a scanning device for mass screening of female individuals for breast cancer [13]. Interestingly, Wild and Reid also discussed potentially dangerous effects of this technology on human tissues, reporting the lack of adverse effects on freshly excised biological tissue and on the exposed brain of animals, as well as the lack of any sensation of discomfort or heating in a self-experiment involving a 30-minute exposure of the arm of one of the two researchers to the high-frequency US pulses [9,10,14].

Of general interest are also the proposals of Wild and Reid for the terminology of the new technology. Originally, they used the term Ultrasonoscope for the transducer and coined the terms Ultrasonography and Ultrasonogram. Later, they suggested calling the US probe echoscope by analogy with the stethoscope, the electronic recording system echograph, and the recordings echograms to match the terminology of electrocardiography. The entire method of recording reflections of US waves from biological tissues was named echography by Wild and Reid in 1952 and suggested, that the technique of echography will be "applicable to tumors at all accessible sites" [8-10].

In 1954, Wild presented his US breast imaging work at his old home, the Middlesex Hospital in London, inspiring Ian Donald, among others [3]. In his lecture he also discussed how US might be applied to the lower abdomen. Wild showed Donald examples of some of his A-mode and cross-sectional US images. They also discussed the possibility of using US to image the gravid uterus. Wild suggested to use lower frequencies than the 15 MHz that he had been using.

This is the link to other important pioneering steps of clinical US in obstetrics and gynaecology going back to the year 1955, when the Regius Chair of Midwifery at Glasgow University, Professor Ian Donald, (recognized as the father of diagnostic US in obstetrics and gynaecology) visited the Research Department of the boilermakers Babcock & Wilcox in Renfrew. Here he was given a demonstration of the ultrasonic metal flaw detector Mark IV and watched as the technicians checked the device by bouncing the US beam off their thumbs and shins, allowing signals from the bones to be visualized. Donald was familiar with sonar from his service in the Royal Air Force, he wanted to look 'behind the iron curtain of the maternal abdominal wall' [15,16]. So, at a second visit to Babcock & Wilcox, he took with him some lumps of tissue, such as fibroids and ovarian cysts, which had recently been removed from patients in his department and carried out some experiments with an industrial ultrasonic metal flaw detector on these tumours. Later he formed a link with Kelvin Hughes Ltd, and particularly with the young technician Tom Brown and Dr. John MacVicar, later Professor of Obstetrics and Gynaecology at the University of Leicester. Together they performed an intensive investigation into the value of US in differentiating between cysts, fibroids and any other intra-abdominal tumours [17].

Early results were disappointing, and the enterprise was greeted with a mixture of scepticism and ridicule. However, a dramatic case where US saved a patient's life by diagnosing a huge, easily removable, ovarian cyst in a woman who had been diagnosed as having inoperable cancer of the stomach, made people take the technique seriously. 'From this point', Ian Donald wrote, 'there could be no turning back' [18]. Looking back to this turning point of his professional career and of the history of US he wrote in 1974: 'The 21st July I955 will always remain one of the sunniest and most important days in my life, when we took down to a factory research department in Renfrew two cars whose boots were loaded with recently excised fibroids, large, small, and calcified, and a very large ovarian cyst. My engineering friends

thoughtfully produced a very large lump of steak as the control material. All I wanted to know, quite simply, was whether these various masses differed in their ultrasonic echo characteristics. The results were beyond my wildest dreams and even with the primitive apparatus of those days clearly showed that a cyst produced echoes only at depth from the near and far walls, whereas a solid tumour progressively attenuated echoes at increasing depths of penetration' [18].Tom Brown, at the age of 24, invented and constructed with Ian Donald the prototype of the world's first Compound B-mode contact scanner in 1957. The transducer operated at 2.5 MHz. The prototype was progressively improved to become the Diasonograph® manufactured commercially by Smith Industries of England which had taken control of the Kelvin Hughes Ltd in 1961 [16,17].

In 1958 Donald, MacVicar, and Brown published in the Lancet their first clinical results of tumour differentiation in 100 patients [19]. In 1959 Ian Donald noted that clear echoes could be obtained from the fetal head and began to apply this information for prenatal diagnosis [3].

In the years that followed, diagnostic US in gynaecology and obstetrics gained increasing acceptance by several scientists. In 1967 Selezneva from Russia published a paper on "Experience in the use of ultrasonics in the diagnosis of uterine and adnexal tumours" [20]. At the same time Alfred Kratochwil at the Second University Frauenklinik in Vienna, Austria, started research on placental localization with an A-mode scanner made by Kretztechnik in Zipf, Austria [21]. Between 1962 and 1964 in Germany the engineers Richard Soldner and Walter Krause, working for Siemens in Erlangen, developed the first fast B-scanner [22]. Holländer had the opportunity to test the first prototype of what later became the Vidoson (1967) [23]. In 1967 Holländer and his group reported on the obstetric significance of ultrasonic diagnosis [23]. In 1968 Holländer also demonstrated the value of this fast B-scanner for the diagnosis of intra-abdominal tumours [24] and Jerzy Groniowski from Poland [25] published a paper on gynaecological US.

In the late sixties and in the seventies, many other European doctors undertook research on clinical US in obstetrics and gynaecology including Manfred Hansmann in Germany, Malte Hinselmann in Switzerland, Emil Reinold and Alf Staudach in Austria, Stuart Campbell in Great Britain, Salvator Levi in Belgium, Francis Weill in France, Fernando Bonilla-Musoles in Spain, Alberto Zacutti and CA Brugnoli in Italy, Jury Wladimiroff in the Netherlands, Bertil Sunden in Sweden, Penti Jouppila and Olli Piiroinen in Finland, Hans Henrik Holm and Jens Bang in Denmark, Asim Kurjak in Croatia, Miklós Falus and Mátyás Sobel in Hungary, Alfred Kotásek in Czechoslovakia, Sergey Yu Sokolov in Russia, and several others.

The First World Congress on Ultrasonic Diagnostics in Medicine took place in Vienna, Austria, on June 2-7, 1969. This conference was an interdisciplinary meeting including neurology, ophthalmology, internal medicine, obstetrics and gynaecology, cardiology, physics and techniques of US. In the field of obstetrics and gynaecology, 13 groups from gynaecology and obstetrics departments from all over the world presented results of sonographic imaging. Only three of those used the Vidoson, while the rest worked with compound scanners [23].

In 1972, 13 European Ultrasound societies met in Basel, Switzerland to form the European Federation of Societies for Ultrasound in Medicine and Biology (EFSUMB) [2].

Ultrasound in obstetrics

Anatomy

In 1967 Kratochwil and Eisenhut from Vienna, Austria, were the first to report the detection of fetal heart activity using US [26]. Zacutti and Brugnoli from Italy reported on the value of ultrasonic scanning in the diagnosis of ectopic pregnancy 1970 [27]. In 1971 Emil Reinold from Vienna, Austria, published a paper on fetal movement during early pregnancy [28] and in 1972 Holländer published his first book "Ultrasound Diagnostics in Pregnancy" [29]. In 1980 Lindsey D. Allan et al [30] published a study on echocardiographic and anatomical correlates in the fetus.

Biometry

In the seventies and eighties many groups started working on biometric measurements of the embryo and the fetus. In 1973, Robinson presented crown-rump measurement in the first trimester [31]. Several European working groups followed with different fetal measurements (Table I).

Table I. Examples for biometric measurements of fetal parameters.

Cephalometry	[32-37]
Abdomino-/thoracometry	[34,38-41]
Long limb bones	[42-45]
Assessing gestational age	[46]
Brain ventricle diameter	[47]
Cerebellar diameter	[47,48]
Orbital diameter	[49]
Thymus	[50]
Heart	[51]

Fetal measurements were also used to develop formulas to calculate the fetal weight [39,52-55] and to detect fetal growth retardation [56,57]. Nowadays fetal growth charts for many fetal parameters have been developed by different European working groups [47,58-64].

Detection of fetal malformations

The ability to detect fetal malformations by US was an enormous step in prenatal diagnosis. In 1968 Hofmann and Holländer reported on 9 cases of hydrops fetalis universalis [65]. Over the following years many publications on the detection of fetal malformations followed [66-72]. As a result of developments in US technology over the last 30 years, with development of high-resolution probes and high image quality many fetal malformations and genetic abnormalities can now be diagnosed not only in the second [73-78] but also in the first trimester [79-85]. Currently there are more than 54,000 publications on the sonographic diagnosis of fetal malformations listed in PubMed.

Screening programs

Based on the positive results of the ultrasonic routine screening program of a pregnant population in Malmö, Sweden [86], the world's first general screening program proposed by Manfred Hansmann and Bernhard-Joachim Hackelöer with two US examinations for every pregnant woman was introduced in Germany in 1979 [87]. The primary aim was early verification of gestational age, early detection of multiple or abnormal pregnancy (e.g., missed abortion, ectopic pregnancy, anencephalus), and detection of growth abnormalities. In 1981 Hansmann published the first multi-level standards (level I, II and III) for US examinations during pregnancy [88] which were introduced by the obstetrics and gynaecology section of the German Society for Ultrasound in Medicine (DEGUM) in 1982. This society was founded in 1971 by 15 scientists from various disciplines as the German Working Group for Ultrasound Diagnostics (DAUD) and renamed in 1978 into DEGUM, which was divided into sections according to the specialist areas that dealt with US diagnostics [89]. Since that time, local, national, and multicenter screening programs have been introduced in many countries for early detection of abnormal pregnancy and in particular in early detection of structural and genetic abnormalities of the fetus [90-96].

One major step in early screening for genetic abnormalities was the introduction of a "First trimester screening" by Nicolaides and his group in London (Fetal Medicine Foundation London) [97,98]. They demonstrated that an increased nuchal translucency at 10-14 weeks of gestation is correlated with a high risk of chromosomal abnormalities. After developing a risk calculator, they were able to estimate the risks for trisomies 21, 18 and 13 at 11-13 weeks' gestation by a combination of maternal age, fetal nuchal translucency thickness, and maternal serum free ß-hCG and PAPP-A. A similar first trimester risk calculation program (PRC = prenatal risk calculation) but with a different algorithm was introduced by the Fetal Medicine Foundation Germany in 1997 [99]) with the latest version 3.0 released at the end of 2013 [100].

However, increased nuchal translucency is not only seen in chromosomal defects [101] but also in association with several structural defects including cardiac ones [85,102,103].

Physiologic observations

With the development of real-time scanners some scientific groups started to study fetal body and breathing movements [104-108]. Fetal behaviour reflects the activity of the fetal central nervous system. Understanding fetal behaviour is crucial for the understanding of normal fetal well-being and in the evaluation of the possibly compromised fetus [109].

Doppler studies

In Europe, early Doppler US in obstetrics started in the 1970's. Pourcelot from Tours, France introduced the resistance index in 1974 [3,110]. Gosling and King from Guy's Hospital, London described in the same year the pulsatility index [111]. The Drumm group in Dublin, Ireland described the use of the A/B ratio in 1980 [3].

By 1977 FitzGerald and Drumm from Dublin [112] reported on fetal umbilical blood-flow patterns, observed from as early as 12 weeks' gestation. In subsequent years many scientific groups published results on Doppler US of the arterial and venous vascular system of the fetus [113-118]. Doppler US was mainly used for the surveillance of high-risk pregnancies and in the recognition of placental insufficiency [119]. Nowadays Doppler US is used in evaluating fetal and maternal circulation in all pregnant women and in particular for the evaluation of fetal hypoxia [120,121] and in screening for preeclampsia [122] and fetal growth restriction [123,124].

Invasive procedures

US has had an important role in improving the safety of invasive procedures during pregnancy. In 1967 Hofmann, Mast and Holländer [125] reported on the value of sonographic placental localization before amniocentesis. In 1972 Bang and Northeved [126] reported on 68 amniocenteses with a special puncture transducer. This transducer had a central channel for the needle which allowed puncture of the amniotic cavity with needle control and without passing through the placenta. Over the following years several companies developed needle-guide adapters for the US probes. Due to the fact that it was difficult to keep the equipment sterile and that a correction

of the needle direction was hardly possible, most doctors used an assistant who held the probe with one hand and they did the puncture freehand. Another technique was to keep the probe in one hand and to guide the needle with the other hand. Both freehand techniques allowed correction of the needle direction under US control during the puncture. In twin pregnancies where it was necessary to mark the first cavity in order to identify both sacs, 1-2 ml of indigo carmine or methylene blue were injected into the first sac after aspiration of amniotic fluid [127]. This procedure was abandoned after the development of high-resolution probes which enabled a precise differentiation of both amniotic cavities. In case of severe oligohydramnios without evidence of rupture of the membranes, amniocentesis with infusion of fluid into the amniotic cavity significantly improved US visualisation of the fetus [128].

Other US guided diagnostic procedures during pregnancy include transvaginal [129,130] or transabdominal chorionic villus sampling [129-131], fetoscopy [132,133], puncture of the umbilical vein (cordocentesis) [134,135] or puncture of the umbilical vein inside the fetus as an alternative to cord needling [136], and puncture of the fetus in case of hydrothorax for fluid aspiration [137], urinary tract obstruction for urine analysis [138] or large ovarian cyst for hormone analysis [139].

Fetal therapy

As early as 1972, Hansmann reported on a specific intrauterine therapy in two cases of severe erythroblastosis. After directing the transfusion needle into the fetal peritoneal cavity under control of ultrasonic fast B-scan motion picture (Vidoson 635, Siemens West-Germany), he carried out intrauterine transfusions [140].

With the advent of real-time US and better image quality, several US controlled needling procedures were used for fetal therapy: Puncture of the umbilical vein for fetal blood transfusions in severe Rhesus disease [141], platelet transfusions in severe alloimmune thrombocytopenia [142], or medical treatment of severe fetal tachyarrhythmias via intraperitoneal administration of antiarrhythmic drugs [143]. Other US controlled procedures were shunt insertions to decompress cerebral ventricles [144] hydrothorax [145] or urinary tract obstructions [146]. However, some of these procedures were discontinued because of procedure related complications or deterioration of the fetal situation. In particular shunting of hydrocephalus was abandoned after it was discovered that a large percentage of fetuses with hydrocephalus had undetected cerebral malformations and associated anomalies [147].

Further US controlled fetal therapies were successfully introduced including laser treatment in twin-to-twin transfusion syndrome [148,149] and endoscopic tracheal balloon occlusion for diaphragmatic hernia [150].

Ultrasound in gynaecology

One of the most important pioneers in gynaecological US was Alfred Kratochwil from the Second University Frauenklinik, Vienna, Austria. Inspired by the work of Ian Donald he started in the late sixties to use a proprietary vaginal scanner from Kretztechnik, Austria to explore the female pelvis. Very early on he noticed that the examination of intrapelvic organs could be significantly improved by passing US transducers into natural body orifices so that the region of interest could be scanned at closer range [151]. The first transvaginal scanner from Kretztechnik (1968) was an A-mode-type transducer linked to a mechanical system that allowed longitudinal motion and 360° rotation of the transducer. However, the real value of transvaginal sonography (TVS) was not demonstrated until 1985 when Kretztechnik, Austria produced their first real-time mechanical vaginal sector transducer with a scan angle of 240°. In the meantime, gynaecological US examinations were performed with abdominal probes. This approach had two disadvantages. First, the patients are required to have a full urinary bladder which often causes discomfort and secondly the image quality is seriously compromised in obese patients.

Pelvic anatomy

In 1975 Piiroinen [152] reported the size of the non-pregnant uterus in women of child-bearing age. Demonstration of ovaries and follicular monitoring was introduced by B-J Hackelöer. Together with HP Robinson he published a paper on abdominal ultrasonic demonstration of follicle and corpus luteum development in the normal menstrual cycle and its relation to hormone profiles in 1979 [153]. Sonographic size of uterus and ovaries, measured by transvaginal US in pre- and post-menopausal women was published by Merz et al in 1996 [154].

Pelvic masses

The advent of higher frequency transvaginal probes (5-7.5 MHz) TVS enabled a better discrimination between benign and malignant pelvic masses [155]. Due to the good accessibility of the uterus to sonographic imaging, transvaginal US has become the method of choice for detecting endometrial carcinoma [156-159]. For the evaluation of cervical cancer, transvaginal US has also gained increased attention in recent years, because it is highly accurate in detecting tumour presence and in evaluating local extension of disease [160,161].

In Europe early attempts were made to develop scoring systems for the assessment of ovarian tumours [162,163]. The introduction of transvaginal colour flow

imaging allowed the detection of angiogenesis in tumours [164-167] and new scoring systems included Doppler parameters into their evaluation [168,169].

In 2000 the International Ovarian Tumour Analysis (IOTA) Group [170] published terms, definitions and measurements to describe the sonographic features of adnexal tumours. In 2005 Timmerman et al [171] reported on a logistic regression model to distinguish between benign and malignant adnexal masses. In 2006 Valentin et al [172] published a paper on US characteristics of different types of adnexal malignancies and in 2010 Timmerman et al [173] summarised simple US rules to distinguish between benign and malignant adnexal masses before surgery. Since then, many other papers on the assessment of ovarian and other pelvic tumours have been published [174-177].

Ovarian cancer screening

Ovarian cancer has a poor prognosis with the majority of women diagnosed at an advanced stage of the disease. As early as 1989 Campbell et al [178] reported on transabdominal US screening for early ovarian cancer with a high sonographic detection rate for ovarian cancer at stage 1a and 1b and an overall false positive rate of 2.3%. However, in the recently published results of the large UK Collaborative Trial of Ovarian Cancer Screening (UKCTOCS) the conclusion was that the screening did not significantly reduce ovarian and tubal cancer deaths. Thus, general population screening cannot be recommended [179].

Transvaginal puncture of simple ovarian cysts

US-guided aspiration of a simple ovarian cyst or ascites in the cul-de-sac is a diagnostic and alternative therapeutic procedure that allows cytological examination and may reduce the need for surgery [180-182].

TVS in reproductive medicine

Due to the close distance to the ovaries, TVS soon became a standard procedure in follicle monitoring, control of endometrium, and oocyte retrieval via transvaginal puncture [183,184]. Another standard procedure in the investigation of infertility is hystero-salpingo-contrast sonography (HyCoSy), to control tubal patency [185].

3D/4D ultrasound in obstetrics and gynaecology

Even though initial experimental 3D US studies had already been published by Szilard in 1974 [186], the clinical application of 3D US only started several years later with the first commercial 3D US unit (Combison330) introduced by Kretztechnik, Zipf, Austria, in 1989 (fig 1) [187,188]. This unit was equipped with 3D probes which were matched to the system (so-called internal system). After automatic volume acquisition it was possible to display the three orthogonal two-dimensional image planes at the same time on the monitor. Parallel to that

Fig 1. First commercial 3D ultrasound unit (Combison 330) introduced by Kretztechnik, Zipf, Austria, in 1989 with automatic abdominal 3D probe with a relatively large size.

system so-called external 3D systems were also developed (e.g., TomTec, Echotech, InViVo-system), in which free hand volume acquisitions could be performed using any conventional 2D probe. An electromagnetic position sensor had simply to be attached to the probe so that the transducer position and movements could be recorded on the basis of changes in the magnetic field. After transfer of the individual 2D images to a workstation, the images and their individual positions were assembled by a computer program to form a volume. The disadvantage of external systems is that the distances between the individual 2D image planes are usually not identical due to the manual probe guidance and that 4D display is not possible [188]. As a result, all modern US systems use 3D transducers with automatic volume acquisition providing the examiner with high quality images.

Many experienced 2D US examiners were initially sceptical of this new technique and 3D US was viewed as a difficult, inconvenient, and unnecessary method [188]. However, several European 3D pioneers such as Eberhard Merz (Germany), Alfred Kratochwil (Austria), Bernard Benoit (France), Daniel Rotten (France), Jean-Marc Levaillant (France), Fernando Bonilla-Musoles (Spain), Horst Steiner (Austria), Rabih Chaoui (Germany) and Kai-Sven Heling (Germany) believed in this technology.

The first World Congress on 3D Ultrasound, organized by Eberhard Merz, took place in Mainz, Germany on September 5 - 6, 1997 (fig 2a) and one year later an exciting 3D book was published (fig 2b) [189]. Due to technical improvements, development of different 3D display modes, simplification of operation, faster image rendering due to greater computer processing power, and significant improvement in image quality, 3D US has made tremendous progress since that time (fig 3). 3D/4D US has been shown to be not only a valuable supplemen-

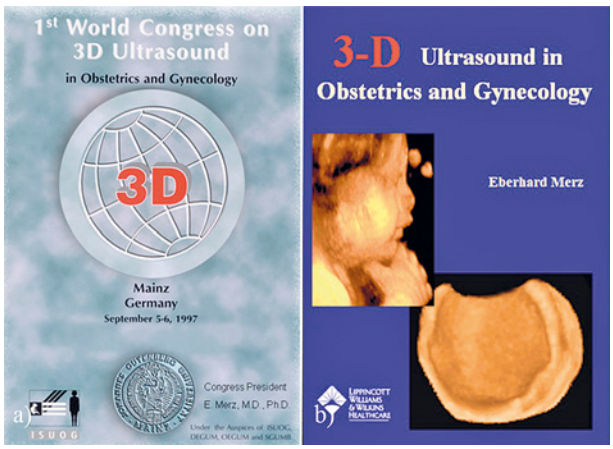

Fig 2. a) Poster of the 1st world congress on 3D ultrasound in obstetrics and gynecology (Mainz Germany, 1997); b) 3D ultrasound book in obstetrics and gynecology, published in 1998 [174].

tary method to conventional 2D US but has confirmed it as being essential for the precise demonstration of suspicious findings in obstetrics and gynaecology.

Of course, many diagnoses can be made using 2D US. However, areas of interest can only be visualised on individual image planes [190]. In contrast to 2D US, 3D US provides several imaging modes that are used in prenatal diagnosis and in gynaecology, depending on the particular issue: multiplanar mode, tomographic mode, surface mode, transparent mode, HDlive mode and some more. A further significant advantage of 3D US for the examiner is that three-dimensional structures are not only shown three-dimensionally but can also be digitally stored without quality loss in the form of 3D images, volumes, or 3D sequences [191]. Moreover, 3D/4D US allows virtual US examinations and the spatial display of structures that

1994 2021

Fig 3. Demonstration of the improvement in surface image quality between 1994 and 2021: lateral cleft lip (surface view), Combison 530, Kretztechnik, 1994 and lateral cleft lip (HD live surface view), Voluson 10, GE, Zipf, Austria, 2021.

can be assessed more clearly in rotation mode and using movable light sources. 4D US provides the examiner with surface or transparent images in real-time, allowing precise studies on fetal movements [192]. Last but not least, 3D images are also easier for patients to understand than individual sectional planes.

Thirty-three years after the introduction of 3D US in obstetrics and gynaecology, 3D/4D US has become globally available and many papers have been published showing the benefits of routine 3D and 4D US in prenatal examinations [78,191-205] and gynaecologic diagnosis [206-208] and also in networking of US volumes [209].

Ultrasound and safety

The question whether US in pregnancy is harmful has been raised many times since the introduction of US in prenatal diagnosis [210,211]. Increasing numbers of experimental studies and publications on this topic have resulted in the EFSUMB setting up a permanent committee for reviewing and evaluating all these studies. This "European Committee for Medical Ultrasound Safety" (ECMUS) produces an annual publication of the results of these reviews in the form of statements and recommendations regarding limit values, mode-specific sound emissions, and safe examination techniques [212]. Similar evaluations and statements have also been published in Europe by the British Medical Ultrasound Society [213] and the ISUOG [214].

Based on the currently ECMUS statements and after more than 40 years of searching for US-induced bioeffects, it can be stated that today's US methods do not have any side effects for embryos and fetuses when applied properly. There is theoretically the possibility of undesired effects like cavitation or an increase in temperature but only when US is incorrectly used, i.e., in the case of excessively long use of high intensities and/or a high sound pressure, excessively long application of Doppler US, use of contrast agents, or in the case of "a pregnant woman with a high fever". Particularly in the case of pulsed Doppler US, the ALARA principle (As Low as Reasonably Achievable) should be taken into consideration to prevent a thermal effect by keeping the local exposure as low as possible. Since incorrect application of US can be ruled out with today's US devices if the examiner has received the appropriate medical training, diagnostic US in pregnancy can be classified as safe from a scientific and clinical standpoint [210]. This level of safety applies to 2D US as well as 3D US, which is inherently associated with particularly low emission values. Moreover, in the case of 3D US, the majority of the

diagnostic process is performed using stored data. During this process, the patient does not come in contact with the US transducer and does not even have to be present [210].

For a detailed overview on safety aspects of diagnostic US see the publications of Dudwiesus and Merz [211,215].

Conflict of interest: none

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