BIOSCIENCES BIOTECHNOLOGY RESEARCH ASIA, August 2015. Vol. **12**(2), 1743-1750

Comparative Assessment of 24-hour Fetal Monitoring Methods Based on Cardiac Rhythm

Artem Shamilyevich Bureev[1], Dmitry Sergeevich Zhdanov[1,3], Nadezhda Nikolaevna Zilberman[3], Ekaterina Yurievna Kiseleva[1] and Sergey Yurievich Yuriev[2]

[1]Diagnostika + Limited Liability Company, office 406, Akademichesky Avenue, Tomsk, Russia, 634055
[2]Siberian State Medical University, 634050, Moskovsky Trakt, Tomsk, Russia, 634050
[3]National Research Tomsk State University, 634050, Tomsk, Russia, Lenina avenue, 36

DOI: http://dx.doi.org/10.13005/bbra/1838

(Received: 10 April 2015; accepted: 22 June 2015)

The problem of monitoring maternal and fetal health and developing devices for 24-hour monitoring is topical at the moment taking into account a reduction in the level of fertile-age women's health and changes in the concept of perinatal medicine with reconsideration of live birth criteria. Such devices will allow significantly reducing the antenatal fetal mortality rate due to continuous monitoring over the state of fetus regardless of mother's location. The goal of this article is performing an analytical review of existing methods used to assess the state of the fetal cardiovascular system in order to reveal their benefits and drawbacks. Speaking about existing methods used to assess the state of the fetal cardiovascular system, it is possible to single out auscultation, fetal electrocardiography, cardiotocography (the current gold standard), magnetocardiography and phonocardiography. Among all the existing methods assessing the state of fetus based on the cardiac rhythm, only fetal electrocardiography and cardiotocography are realized in the form of portable 24-hour monitoring devices. These devices have certain drawbacks. In the authors' opinion, the most promising method for 24-hour fetal monitoring based on the cardiac rhythm is phonocardiography. When introducing this method into medical practice, it is necessary to solve the task of receive stable signals in case of various types of fetal presentation and mother's anthropometric data.

Key words: Fetal monitoring, fetal electrocardiography, cardiotocography, Magnetocardiography, phonocardiography, auscultation.

Thirty years ago, intrauterine fetal death was diagnosed, if fetal movements stopped and auscultation detected no fetal heartbeats. Twenty years ago, it was nonsense to perform caesarean section in order to save a fetus. Ten years ago, a critical state of fetus could be detected by means of ultrasound fetometry, Doppler sonography, cardiotocography; however, there was no adequate methodological base and equipment to nurse very immature infants. Nowadays the primary trend of perinatal medicine has been changed in the Russian Federation. Delivery in favor of fetus has become a routine practice. Since January 1, 2012, the following initial live birth criteria have been used: week 22 of intrauterine development and newborn's body mass of 500 g[1]. The country accumulates experience in nursing extremely low-birth-weight infants.

The Russian Federation has set a goal to reduce the rate of maternal and infant mortality in no less than 2 times by 2025 [2].

The rate of infant mortality has reduced

* To whom all correspondence should be addressed.

from 18 per 1,000 live births in 1992 to 7.3 per 1,000 live births in 2012 in the Russian Federation. However, it is still relatively high (Monaco – 1.8; France – 3.4; Belgium – 4.28; Hungary – 5.24).

One of the key criteria of outpatient perinatal institutions' work is the absence of antenatal fetal death cases[3]. Therefore, a decrease in the rate of antenatal mortality, i.e., antenatal protection of fetus, is a reserve for the reduction in the stillbirth rate.

A solution for this situation can be either long-term inpatient hospitalization of high-risk pregnant women or the use of substituting technologies. In order to increase the efficacy of such technologies, it is necessary to develop special tools, which will allow:

a) guaranteeing continuous control over the state of fetus;
b) minimizing the interval of time between the appearance of an aggravation in the state of fetus to provision of emergency medical care;
c) reducing the number of pregnant women's groundless hospitalizations and decreasing pregnant women's hospitalization period;
d) eliminating polypragmasy, reducing medical expenses and the number of adverse events;
e) significantly reducing the risk of antenatal fetal death in outpatient settings.

MATERIALS AND METHODS

The most complete information on fetal development can be received by means of analyzing its cardiac activity[4].

The first data on fetal heartbeats were received by French physician Marsac in the XVII century[5]. However, his observations went unnoticed until 1818, when Swiss surgeon Francois Mayor reported the presence of fetal heart sounds when he placed his ear on the maternal abdomen in an attempt to hear the fetus splash about in the liquor amnii. Three years later, Lejumeau Kergaradec described both the fetal heart tones and the uterine souffle. Also, he suggested auscultation to be of value in the pregnancy management. Until the middle of the XX century, the stethoscope was the only tool to study the fetal cardiac rhythm[6].

Auscultation is still the most common method for determining the cardiac activity[7, 8], since it is one of the cheapest and simplest technique for registering fetal heartbeats. However, the accuracy of results obtained does not meet up-to-date requirements, which is connected with a high probability of physician's subjective mistakes when assessing the frequency and rhythmicity of cardiovascular contractions in a short period of time.

In 1906, Einthoven described the use of galvanometer for registration of adults' cardiac activity. In five years, M. Kramer registered fetal electric activities by means of invasive electrocardiography with the use of abdominal and vaginal electrodes[9, 10].

In the fifties of the XX century, physicians started using abdominal electrocardiography in order to assess the fetal cardiac rhythm. Edward Hon proposed to use a three-electrode scheme, which allowed obtaining fetal electrocardiogram (ECG) by means of singling it out from the registering mixed signal of mother's electrocardiogram[11].

In the sixties-eighties, a lot of attempts were made to obtain authentic fetal ECG from the mixed signal registered on the mother's abdomen both in foreign countries[12-14] and in the USSR[15,16]. However, the then existing level of technical development did not allow obtaining high-quality electrocardiograms. It is connected with the fact that the pregnant woman's ECG amplitude is at least 100 times higher than the fetal ECG signal. Also, there are a lot of noises and artifacts in the process of registration. New methods for extracting fetal ECG signals have emerged over the past 20 years. Some of them are under development at the moment, which is reflected in some research teams' publications[17-21].

Nowadays the independent component analysis and adaptive compensation of interference and mother's signals are used to single out fetal ECG from the mixed signal registered on the mother's abdominal surface[22]. These methods are designed to assess the fetus' cardiovascular system in inpatient settings; however, they do not allow monitoring the state of fetus on a 24-hour basis in outpatient settings.

Despite this fact, these techniques are actively developed; there are research studies focused on the development of new devices that allow performing more accurate and effective diagnostics of the fetal cardiovascular system.

A Ukrainian research team proposed to use the method of singling out fetal ECG from the mixed signal registered on the pregnant woman's abdominal surface by means of blind signal separation[23, 24]. Several research studies confirmed a sufficient quality of the fetal ECG data obtained[25, 26].

The researchers from Yekaterinburg (Russia) also work on the techniques for registering fetal electrocardiographic signals[27, 28, 29]. Fetal ECG is registered by means of a high-resolution ECG unit. However, signals are registered in a semi-automatic mode with further visual assessment of the recording quality.

The scientists from Tomsk (Russia) also developed a device allowing registering fetal heartbeats by means of abdominal electrodes[30]. These signals were also processed with the help of blind signal separation. The authors conducted several research studies, and the research findings confirmed the fact that this device could be used as a diagnostic tool on a par with cardiotocography[31, 32, 33].

The research team from Samara proposed a device to register electrical forces of the fetal heart[34, 35]. Due to the specific location of electrodes, registered signals of electrical forces of the fetal heart contain significantly weakened R-waves of mother's ECG, which increases a probability of proper registration of fetal R-waves up to 0.95. However, it is possible only under the condition of the additivity of interferences, which rarely takes place in practice. Also, there is a device for non-invasive fetal electrocardiography[36]. The authors developed a device to register fetal ECG by means of electrodes located on the pregnant woman's abdominal surface. This device allows registering cardiac activity in case of multiple pregnancy, which has not been implemented in any of similar devices yet. However, the difficulty of applying electrodes to use this device does not allow using it to monitor the state of fetus.

The authors examine the variability of the cardiac rhythm during pregnancy by means of the ECG analysis that allows accurately registering the QRS complex. Such a location of electrodes allows receiving fetal ECG signals on each electrode[37, 38].

Unfortunately, the ECG method has certain drawbacks connected with the fact that data obtained are characterized with a high level of interferences. It makes it more difficult to analyze such data. The noisiness of data is connected with pregnant women's own electric activities, difficulties in suppressing these signals to obtain data suitable for the fetal diagnostics and presence of vernix caseosa that hinders the passage of electric current.

Despite the above mentioned drawbacks, the ECG technique has an unquestionable benefit – precise detection of the QRS complex that has a significant diagnostic value. It allows more accurately determine the cardiac cycle length[39, 40]. However, it could be very difficult or a pregnant woman to apply electrodes on her own in outpatient settings.

In the seventies of the XX century, a new method for registering fetal cardiac activities was introduced in clinical practice – cardiotocography based on the Doppler Effect[41,42]. Cardiotocography (CTG) implies registration of changes in the number of fetus' cardiac contractions together with changes in contractive activities of the uterus and movements of the fetus.

Cardiotocography registers the cardiac activity of the fetus, contractive activity of the uterus and numbers of fetus' movements[43].

Pathologic rhythms can be registered since week 20 of pregnancy[44]; however, CTG indicators can be criteria for initiating therapeutic measures to prevent fetal asphyxia without the risk of significant hyperdiagnostics since week 30 only. The regulations on medical care for pregnant women limits monitoring over the state of fetus to 2 cardiotocograms[45]. If fetal distress signs are detected, a pregnant woman is hospitalized to a medical institution, and up to 2-3 CTG procedures are performed in order to assess the state of fetus under treatment and choose delivery tactics[46].

Nowadays there are a lot of Doppler-based devices that are used to register the fetal heart rate (HR) (BabyCare, Bionet, South Korea; SonicaidOne, Oxfordmedical, Great Britain, etc.)[47, 48, 49] in inpatient settings.

It is noteworthy that the safety of long-term (for several days) exposure to ultrasonic radiation used in cardiotocography has not been confirmed. The British Royal College of Obstetricians and Gynecologists does not recommend performing cardiotocography on a routine basis, since it does not promote a reduction in the rate of perinatal mortality[50]. Some authors conduct research studies on records of long-term monitoring over the state of fetus by means of cardiotocography in order to analyze changes in the basal rhythm at different stages of pregnancy[51, 52]. Detailed analyses of long-term, periodic CTGs and auscultations allow making a conclusion that long-term CTG is associated with a significant increase in the number of cesarean sections performed[53].

Despite wide distribution of ultrasound diagnostic techniques for the detection of pathologic disorders of fetal heartbeats, they do not provide information on the passage of electric signals through the cardiac conduction system and myocardium, which does not allow detecting certain disorders of the cardiac electric activity. Another technique for the assessment of fetal cardiac activities started developing in parallel with cardiotocography – magnetocardiography (MCG). This method is based on registering the magnetic field generated by the fetal cardiac activity. For the first time ever, fetal MCG (FMCG) was registered by Finnish researchers in 1974 [54]. It is believed that this method is diagnostically valuable, since it provides data on fetal electrocardiographic signals in a non-invasive, passive and contact-free way[55].

FMCG shows standard waves and segments typical of adult ECG (P-wave, QRS-complex and T-wave).

Received signals have a very small amplitude (10^{-14}-10^{-11} T) that is comparable with a background level of the magnetic field at medical institutions[56]. Therefore, MCG was performed only in specially equipped rooms for a long time.

The development of computer technologies allows using software in order to process most signals. That's why one can observe high interest in this technique, including from the viewpoint of fetal diagnostics[57-62].

The primary components of MCG systems are ultra-sensitive sensors-gradiometers. Liquid helium should be used in order to support optimal thermal condition for their work[63].

Despite a good quality of fetal electrocardiograms obtained by means of FMCG, the issue of using MCG on a routine basis to assess the state of fetus remains open, and it will not be solved in the near future. It is practically impossible to monitor the state of fetus by means of MCG because of the unavailability of compact systems. Also, a high price for liquid helium and magnetic screening of premises to conduct this procedure is a serious barrier to wide distribution of this technique.

An alternative method for receiving information on the fetal cardiac activity can be phonocardiography (PCG)[64]. PCG provides information on uterine contractions by means of the pressure sensor and allows performing passive, completely non-invasive records of fetal cardiac contractions[65, 66]. Signals can be registered by means of placing an acoustic sensor on the mother's abdominal surface without the need for using a conductive gel. Phonocardiographic signals allow detecting fetal cardiac pathologies, such as cardiac murmur, premature beats and double/ triple atrial contractions[67]. CTG and other methods do not provide such capabilities[68]. The key problem is often proper recognition of fetal cardiac sounds with reference to every heartbeat and further processing. The noisiness of PCG signals is connected with the following factors[69, 70]:

- the quality of phonocardiographic signals depends on the fetal presentation;
- if a fetus moves, it creates acoustic noises typical of its movement activities specifically;
- when registering acoustic signals, there can be interferences in the form of the noises created by the pregnant woman's gastrointestinal track and cardiovascular system;
- registered acoustic signals can contain environmental noises.

Most early work on the use of PCG to assess the fetal cardiovascular system was devoted to the development of new sensors for qualitative registration of cardiac tones[71, 72]. On the contrary, recent research studies are rather focused on the algorithms to process registered signals[73,74]. Quite often, these methods have a goal to produce the frequency distribution of fetal heartbeats. Moreover, detailed quantitative methods to assess the performance of these methods have not been developed yet, and no reliable results have been received[75, 76].

RESULTS AND DISCUSSION

Nowadays an established set of techniques is used to assess the state of fetus at the antenatal stage of development. They are realized in the form of various hardware and software-hardware complexes. At the same time, a conclusion on the state of fetus in the mother's uterus is based on analyzing the state of its cardiovascular system. Data analyzed are obtained by means of registering electric potentials on the mother's abdominal surface (ECG), reflected ultrasonic waves (CTG), magnetic field (FMCG) and acoustic signals (PCG). Research findings are interpreted by both healthcare professionals themselves (based on their personal knowledge and experience) and with the help of specialized algorithmic software. Despite successful use of the existing methods and techniques, specifically 24-hour fetal monitoring requiring no pregnant women's visits to medical institutions is necessary to achieve a significant reduction in the rate of antenatal fetal mortality. To reach this goal, it is necessary to develop outpatient portable devices for pregnant women. Such devices should perform continues registration and analysis of data on the fetal cardiovascular system, which will allow reacting promptly in case of any aggravations of the state of fetus and eliminating unfavorable impacts.

CONCLUSION

In the authors' opinion, the operating principle of these devices should be based on the registration and analysis of fetal PCG. It is connected with difficulties in using other techniques in portable devices because of the problems with applying sensors on the mother's body, interpreting data received and developing hardware components of these devices from the construction viewpoint. Speaking about the registration and analysis of acoustic data of the fetal cardiovascular system, the key problem will be the development of acoustic sensors that will allow receiving the highest-quality fetal PCG from the mother's abdominal surface. But, it will be next step of research.

ACKNOWLEDGMENTS

The work has been performed under Agreement #14.579.21.0019 on the subject Developing the Device for 24-hour Monitoring over the State of Fetus and Mother during Pregnancy by means of Controlling Parameters of the Cardiovascular System based on Acoustic Data between LLC Diagnostica+ and the Ministry of Education and Science of the Russian Federation.

REFERENCES

1. Almazov, V., Samilyanova, A., Shlyakhto, E., & Klauss, G., Heart Auscultation (p. 232). Saint-Peterburg: Publishing House of the Pavlov First Saint-Petersburg State Medical University, 1996.
2. RF Presidential Decree No.1351 as of 10.09.2007 On Approving the Demographic Policy Concept in the Russian Federation for the Period of up to 2025.
3. Order of the Ministry of Health and Social Development of the Russian Federation No.808n as of October 2, 2009 On Approving the Procedure for Obstetrical and Gynecological Medical Care.
4. Voskresensky, S., Assessments of Fetal State Minsk: Knizhny Dom, 2004; 304.
5. Golyshev, N., Superconductor Magnetocardiographs. Autometry, 1995; **1**: 62-76.
6. Ovsepyan, D., Up-to-date Approaches to Assessment of Fetal Cardiac Rhythm. , Vestnik Khirurgii Armenii n.a. G.S. Tamazyan, 2010; **3**: 39-53.
7. Bassil, H., & Dripps, J., Real time processing and analysis of fetal phonocardiographic signals. Clin. *Phys. Physiol. Meas. Clinical Physics and Physiological Measurement*, 1989; **10**(B): 67-74.
8. Favret, A., & Marchetti, A., Fetal Electrocardiographic Wave Forms from Abdominal-Wall Recordings. Obstetrics & Gynecology, 1966; **27**: 355-362

9. Symonds, E., & Sahota, D., Fetal electrocardiography. London: Imperial College Press, 2001.
10. Demidov, V., Logvinenko, A., & Filimonova, N., Value of Detecting Length of ECG Intervals in Diagnostics of Fetal Disorders. Obstetrics and Gynecology, 1983.
11. Hon, E., & Lee, S., Averaging techniques in fetal electrocardiography. *Medical Electronics & Biological Engineering Med. Electron. Biol. Engng*, 1964; 71-76.
12. Fenici, R., Brisinda, D., & Meloni, A., Clinical application of magnetocardiography. *Expert Review of Molecular Diagnostics*, 2011; **5**: 291-313.
13. Kalakutsky, V., Kalakutsky, L., Belyanin, F., & Manelis, E., Device for Registration of Electric Forces of Fetal Heart. *RF Patent* 2269925, 02.22.2006, 2006.
14. Chakhunashvili, G., Dzhobava, N., & Pruidze, N., Efficacy of Non-Invasive Clinical Methods of Assessment of Cardiovascular System in Perinatology. *Georgian Medical News*, 2004; **7-8**: 64-67.
15. Volpin, E., Diagnostics Capabilities of Fetal Electrocardiographic Examinations. Voprosy Okhrany Materinstva I Detstva, 1965; 10.
16. Dzigua, M., Physiological Obstetrics: Guide. Moscow: GEOTAR-Media, 2013; 432.
17. Kiseleva, E., Tolmachev, I., & Pekker, Y.m Developing Method and Hardware-Software Complex for Monitoring and Non-Invasive Assessment of Mother and Fetus' State of Health at Perinatal Period based on Analysis of Electric Signals from Abdominal Electrodes. Biotekhnosfera, 2010; **1**: 12-16.
18. Bionet, Compact Fetal Doppler. (n.d.). Retrieved May 5, 2014, from http://www.bio2net.com/eng/products/products1_1.asp?idx=193&category=55 &search_type=0&search_word= &page_size= 8&page=1
19. Comani, S., Liberati, M., Mantini, D., Merlino, B., Alleva, G., Gabriele, E., Romani, G. (84). Beat-to-beat estimate of fetal cardiac time intervals using magnetocardiography: Longitudinal charts of normality ranges and individual trends. Acta Obstetricia Et Gynecologica Scandinavica *Acta Obstet Gynecol Scand*, **84**: 1175-1180.
20. Hon, E., & Hess, O., Instrumentation of Fetal Electrocardiography. *Science*, 1957; 553-554.
21. M. Banet, Z. Zhou and K. R. Hunt, Two-Part Patch Sensor for Monitoring Vital Signs. USA Patent US20130109937 A1, 02.05.2013.
22. Mittra, A., Shukla, A., & Zadgaonkar, A., System simulation and comparative analysis of foetal heart sound de-noising techniques for advanced phonocardiography. *International Journal of Biomedical Engineering and Technology IJBET*, 2007; **1**(1): 73-85.
23. Shulgin, V., & Tokarev, A., Technique for Registration and Analysis of Fetal Electrocardiograms during Pregnancy. Radioelectronic and Computer Systems, 2008; **3**: 66-75.
24. Shulgin, V., Pechenin, A., Nasedkin, K., & Lakhno, I. (n.d.). Using the Method of Blind Source Separation to Register Fetal Electrocardiograms. Retrieved June 3, 2015, from http://www.xai-medica.com/articles/report/report.htm
25. Lipponen, J., & Tarvainen, M., Advanced Maternal ECG Removal and Noise Reduction for Application of Fetal QRS Detection. *Computing in Cardiology*, 2013; **40**: 161-164.
26. Shulgin, V., Pechenin, A., Nasedkin, K., & Fedotenko, V. (n.d.). Analysis of Fetal ECG and CRV by means of CardioLab Cardiographic System. Retrieved June 3, 2014, from Fedotenko
27. Kovács, F., & Török, M., Instrument using Parallel Filtering of Acoustic Signals to Record Fetal Heart Rate. *Biomedical Instrumentation & Technology*, 2003; **23**(9), 283-296.
28. Tsyvyan, P., Kovalev, V., Chaschin, G., Tarasova, N., & Kodkin, V., High-Resolution Fetal Electrocardiography. New Capabilities of the Old Method. Ural Medical Journal. *Perinatalogy*, 2008; **12**: 78-80.
29. Várady, P., Wildt, L., Benyó, Z., & Hein, A., An advanced method in fetal phonocardiography. *Computer Methods and Programs in Biomedicine*, 2003; 283-296.
30. Kühnert, M., Hellmeyer, L., W., S., & S., S., Twenty-Four-Hour CTG Monitoring: Comparison of Normal Pregnancies of 25–30 Weeks of Gestation versus 36–42 Weeks of Gestation. *Archives of Gynecology and Obstetrics*, 2006; **275**: 451-460.
31. Pekker, Y., Brazosky, K., Tolmachev, I., Kiseleva, E., Agarkova, L., & Gabitova, N., Device for Registration of Fetal Cardiac Rhythm by means of Abdominal Electrodes. Russia, Patent 79768, 01.20.2009; 2009.
32. Kodkin, V., Tsyvyan, P., Filchenko, N., & Dubel, A., Device for Non-Invasive Diagnostics of State of Fetus at Antenatal Period. Russia, Patent No. 2428108, 09.10.2011, 2011.
33. Pekker, Y., Kiseleva, E., & Tolmachev, I., Using Fetal Beat-to-Beat Ratemetry as Additional Criterion to Assess Severity of Fetal Hypoxia during Pregnancy complicated with Hyperandrogenism. News of Southern Federal University. *Technical Sciences*, 2009; **109**(8):

161-165.

34. Pekker, Y., Tolmachev, I., & Kiseleva, E., Using Fetal Beat-to-Beat Rate Detection as Additional Criterion to Assess Severity of Fetal Hypoxia during Pregnancy complicated with Hyperandrogenism. *Siberian Medical Journal*, 2010; **25**(4-2): 70-72.
35. Tsurkan, S., Kalakutsky, L., & Belyanin, F., Method for Diagnostics of Fetal Hypoxia during *Pregnancy. Russia,* Patent 2324422, 07.03.2006, 2006.
36. Kariniemo, V., Ahopelto, J., Karp, P., & Katila, T., The Fetal Magnetocardiography. *J. Perinat. Med*, 1974; **2**: 214-216.
37. Taylor, M., Smith, M., Thomas, M., Green, A., Cheng, F., Oseku-Afful, S., Gardiner, H., Non-invasive fetal electrocardiography in singleton and multiple pregnancies. BJOG: An International Journal of Obstetrics and Gynaecology BJOG: *An Internal Journal of Obs Gyn*, 2003; **110**: 668-678.
38. Lakhno, I., Non-Invasive Computer Fetal Electrocardiography vs. Fetal Cardiotocography: First Experience in Ukraine. Meditsina Neotlozhnykh Sostoyaniy, 2012; **40**(1): 101-105.
39. Peters, C., Laar, J., Vullings, R., Oei, S., & Wijn, P. (n.d.). Beat-to-beat heart rate detection in multi-lead abdominal fetal ECG recordings. *Medical Engineering & Physics*, **34**(3): 333-338.
40. Chen, D., Durand, L., & Lee, H., Time-frequency analysis of the first heart sound. Part 1: Simulation and analysis. Med. Biol. Eng. Comput. *Medical & Biological Engineering & Computing*, 1997; **1**(1): 306-310.
41. Graatsma, E., Jacod, B., Egmond, V., Mulder, E., & Visser, G., Fetal Electrocardiography: Feasibility of Long-Term Fetal Heart Rate Recordings. BJOG: *International Journal of Obstetrics & Gynaecology*, 2009; 334-338.
42. Westerhuis, M., Strasser, S., & Moons, K., Intrapartum Fetal Monitoring: From Stethoscope. *Ned. Tijdschr. Geneeskd*., 2009; **153**, 259-259.
43. Laar, J., Warmerdam, G., Verdurmen, K., Vullings, R., Peters, C., Houterman, S., . Oei, S., Fetal heart rate variability during pregnancy, obtained from non-invasive electrocardiogram recordings. Acta Obstetricia Et Gynecologica Scandinavica *Acta Obstet Gynecol Scand*, 2013; **93**: 93-101.
44. Haghpanahi, M., & Borkholder, D., Fetal ECG Extraction from Abdominal Recordings using Array Signal Processing. *Computing in Cardiology*, 2013; **40**: 173-176.
45. Voskresensky, S., and Zelenko, E., Cardiotocography at Antenatal Stage Minsk: BelMAPO, 2010; 60.
46. RF Ministry of Health and Social Development, Standard of Medical Care for Women with Normal Course of Pregnancy. Approved on September 14, 2006, 2006.
47. Order of the Ministry of Health of the Russian Federation as of November 7, 2012 No.572n, On Approving the Standard of Specialized Medical Care in case of Fetal Hypoxia, Insufficient Fetal Development and Other Placental Disorders.
48. Callaerts, D., Sansen, W., Vandewalle, J., Vantrappen, G., & Janssens, J., Description of a real-time system to extract the fetal electrocardiogram. *Clin. Phys. Physiol. Meas. Clinical Physics and Physiological Measurement*, 1989; **10B**: 7-10.
49. Oxford Medical, Fetal Heartbeat Detectors – Sonicaid®One. (n.d.). Retrieved May 5, 2014, from http://www.oxford-medical.ru/detectory_serdcebieniya_ploda_sonicaid_one.html
50. West Health Institute, Sense4Baby. (n.d.). Retrieved May 5, 2014, from http://www.westhealth.org/news/press-release-sense4baby-licenses-wireless-fetal-monitor-system
51. On Medical Birth Criteria, Birth Certificate and Issuance Procedure: Order of the Ministry of Health and Social Development of the Russian Federation as of 12.27.2011 No.1687n. (). *Rossiyskaya Gazeta*, **64**; 2012).
52. Künzel, W., Anfänge der Kardiotokographie. Gynäkologe Der Gynäkologe, 2009; **5**: 328-335.
53. Grivell, R., Alfirevic, Z., Gyte, G., & Devane, D., Antenatal cardiotocography for fetal assessment. Cochrane Database of Systematic Reviews Reviews, 1996.
54. National Institute for Health and Clinical Excellence. Nursing Standard, 2008; 30-30.
55. Khamene, A., & Negahdaripour, S., A new method for the extraction of fetal ECG from the composite abdominal signal. IEEE Transactions on Biomedical Engineering IEEE Trans. *Biomed. Eng*., 2000; **47**(4): 507-516.
56. Seki, Y., Kandori, A., Kumagai, Y., Ohnuma, M., Ishiyama, A., Ishii, T., Chiba, T., Unshielded fetal magnetocardiography system using two-dimensional gradiometers. Rev. Sci. Instrum. *Review of Scientific Instruments*, 2008; **79**: 1-3.
57. Polyakova, I., Magnetocardiography: Historical Background, Current State and Prospects for Future Clinical Use. *Creative Cardiology*, 2011; **2**: 103-133.
58. Freeman, R., Fetal heart rate monitoring (4th ed.). Philadelphia: Wolters Kluwer Health/Lippincott Williams & Wilkins, 2012.
59. Wren, C., Cardiac arrhythmias in the fetus and

newborn. *Seminars in Fetal and Neonatal Medicine*, 2006; **1**: 182-190.

60. Strasburger, J., Cheulkar, B., & Wakai, R., Magnetocardiography for fetal arrhythmias. *Heart Rhythm*, 2008; **7**: 1073-1076.

61. Comani, S., Mantini, D., Alleva, G., Gabriele, E., Liberati, M., & Romani, G., Simultaneous monitoring of separate fetal magnetocardiographic signals in twin pregnancy. *Physiological Measurement Physiol. Meas*., 2005; 193-201.

62. Verklan, M., Padhye, N., & Brazdeikis, A., Analysis of Fetal Heart Rate Variability Obtained by Magnetocardiography. *The Journal of Perinatal & Neonatal Nursing*, 2006; **20**: 343-348.

63. Cremer, M., Über die Direkte Ableitung der Aktionstrome des Menschlichen Herzens vom Oesophagus und Über das Elektrokardiogramm des Fetus. Münchener Medizinische Wochenschrift, 1906; **53**: 811-813.

64. Gotye, E., Value of Elevated QRS Complex in Assessment of Functional State of Fetus. *Obstetrics and Gynecology*, 1979; **1**: 57-59.

65. Kovacs, F., Horvath, C., Torok, M., & Hosszu, G., Long-term Phonocardiographic Fetal Home Monitoring for Telemedicine Systems. 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference, 2006; 3946-3949.

66. Kovalev, V., Sivov, V., Komarova, G., & Tsyvyan, P., Diagnostics and Treatment of Fetal Cardiac Rhythm Disorders. *Ural Medical Journal*, 2010; **5**: 53-56.

67. Kovacs, F., Torok, M., & Habermajer, I., A rule-based phonocardiographic method for long-term fetal heart rate monitoring. IEEE Transactions on Biomedical Engineering IEEE Trans. *Biomed. Eng*., 2000; **47**(1): 124-130.

68. Ruffo, M., Cesarelli, M., Romano, M., Bifulco, P., & Fratini, A., An algorithm for FHR estimation from foetal phonocardiographic signals. *Biomedical Signal Processing and Control*, 2010; **5**: 131-141.

69. Chen, J., Phua, K., Song, Y., & Shue, L., Fetal Heart Signal Monitoring with Confidence Factor. 2006 IEEE International Conference on Multimedia and Expo, 1937-1940, 2006.

70. Behar, J., Oster, J., & Clifford, D., Non-Invasive FECG Extraction from a Set of Abdominal Sensors. *Computing in Cardiology*, 2013; **40**: 297-300.

71. Moghavvemi, M., Tan, B., & Tan, S., A non-invasive PC-based measurement of fetal phonocardiography. Sensors and Actuators A: *Physical*, 2006; **107**(1), 96-103.

72. S. Kabakov, Fetal Monitoring System and Method. USA Patent US8694081 B2, 04.08.2014.

73. Martens, S., Rabotti, C., Mischi, M., & Sluijter, R., A robust fetal ECG detection method for abdominal recordings. *Physiological Measurement Physiol. Meas*., 2007; **28**: 373-388.

74. Christov, I., Simonova, I., & Abaecherli, R., Cancellation of the Maternal and Extraction of the Fetal ECD in Noninvasive Recordings. *Computing in Cardiology*, 2013; **40**: 153-156.

75. Rouhani, M., & Abdoli, R., A comparison of different feature extraction methods for diagnosis of valvular heart diseases using PCG signals. *Journal of Medical Engineering & Technology J Med Eng Technol*, 2012; **36**(1): 42-49.

76. Chourasia, V., Tiwari, A., Gangopadhyay, R., & Akant, K., Foetal phonocardiographic signal denoising based on non-negative matrix factorization. *Journal of Medical Engineering & Technology J Med Eng Technol*, 2012; **36**(1): 57-66.