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Cerebral Hemodynamics in Pediatric Hydrocephalus: Evaluation by Means of Transcranial Doppler Sonography

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Abstract

Active, progressive hydrocephalus in children leads to increase of intracranial pressure, dilatation of cerebral ventricles, and decrease of intracranial compliance. These changes lead to disorder of regulation of cerebral circulation and development of cerebral hypoperfusion resulting in the secondary brain damage. Ependymal disruption, periventricular edema, and compression of the periventricular capillaries can be developed. Ischemia of the white matter can be developed due to hypoperfusion. But it is reversible if treated early and adequately. Transcranial Doppler sonography enables to determine hemodynamic parameters of cerebral circulation in various physiological and pathophysiological conditions. As transcranial Doppler sonography has been regarded to be noninvasive and appropriate for bedside treatment, it can also be applied in children at any age. The goal of this chapter is to assess changes of cerebral circulation in children with hydrocephalus and application of data from scientific studies of intracranial dynamics in children with hydrocephalus in clinical practice. The work is also focused on evaluation of impact of intracranial factors on Doppler parameters of cerebral circulation, especially in neonates with hydrocephalus. The ambition of this chapter is to improve indication and timing of drainage procedure in children with hydrocephalus by application of the results and clinical experience in daily clinical practice.

Keywords: cerebral hemodynamics, transcranial Doppler sonography, pediatric hydrocephalus

1. Introduction

Increased accumulation of cerebrospinal fluid in children with hydrocephalus leads to increased intracranial pressure, dilatation of the cerebral ventricles, decrease of intracranial compliance, and reduction of the brain tissue with negative impact on neurological condition of the child and his neurological development in the future. Alteration of cerebral circulation includes compression of the cerebral capillaries, stretching of the cerebral arteries, dysregulation of cerebral circulation, increase of cerebrovascular resistance, and decrease of cerebral blood flow. Progression of damage of the brain tissue results from decrease of blood flow in the brain and cerebral ischemia accompanied by changes in energetic metabolism. To measure the acute reversible cerebrovascular changes, and thus improve indication and timing of drainage procedure in noninvasive way, there is a need for examination technique, which could be used in daily clinical practice. This is the potential of transcranial Doppler sonography. It can analyze blood flow in the cerebral arteries and thus enables to perform noninvasive assessment of hemodynamic parameters of cerebral circulation.

Interpretation of changes in the Doppler curve of the cerebral arteries in pediatric hydrocephalus remains to be a discussed issue. Increase of cerebrovascular resistance of the cerebral arteries due to increased intracranial pressure is reflected in change of blood flow velocity and increased values of qualitative indices in the Doppler curve. Generally, there is good correlation between resistance index and pulsatility index of the cerebral arteries and intracranial pressure. Relationship between intracranial pressure, clinical manifestations of intracranial hypertension, dilatation of the cerebral ventricles, and Doppler parameters of the cerebral arteries is defined by biomechanical properties of the cranium and the brain in various age groups in children. It may be also influenced by many intra- and extracranial factors, which affect cerebral circulation [1]. In critically ill children, several factors are usually combined, which may, but do not have to, affect changes in the Doppler curve of the cerebral arteries. Therefore, cerebral blood flow in this type of patients has to be assessed carefully.

2. Doppler parameters of cerebral circulation in pediatric hydrocephalus

Bada et al. [2] were the first who described *the relationship between Doppler parameters of cerebral circulation and intracranial pressure* in preterm neonates with posthemorrhagic hydrocephalus. The results showed increased resistance index of the cerebral arteries due to increased intracranial pressure [2]. In the same year, Hill and Vople [3] presented results of their research on changes of RI-ACA in neonates with hydrocephalus. In nine out of ten cases, dilatation of the cerebral ventricles was accompanied by increase of intracranial pressure. In all cases, RI-ACA was increased. It was affected mainly by decrease of Ved. After drainage procedure, RI-ACA decreased due to increase of Ved. According to the authors, ventriculomegaly was considered more significant factor influencing hemodynamic parameters of ACA than increased intracranial pressure. Because in most of the cases, dilatation of the cerebral ventricles was accompanied by increased intracranial pressure, it is difficult to differentiate impact of dilatation of the cerebral ventricles from impact of increased intracranial pressure on cerebral circulation [3].

Fisher and Livingstone [4] observed change of parameters of blood flow in the Doppler curve in MCA, ACA, and ICA. The research revealed increase of PI, significant decrease of Ved, and slight decrease of Vsyst before drainage procedure. After drainage procedure, in which functional internal drainage system had been applied, return of hemodynamic parameters to normal range of values was confirmed. However, this change was not accompanied by return of size of the cerebral ventricles to standard values, excluding width of the third cerebral ventricle. Correlation between size of the cerebral ventricles and Vsyst was not proven. Relationship between Ved and size of the cerebral ventricle was intraindividual in its nature. The strongest correlation was measured between size of the cerebral ventricles and pulsatility index. Regarding morphological parameters, width of the third cerebral ventricle showed to be a precise indicator of changes of intracranial volume [4]. It was found out that ACA and MCA have the highest predisposition to early reaction to change of intracranial dynamics [4, 5]. During observation of RI-ACA, RI-MCA and RI-ICA in children with hydrocephalus before drainage procedure as well as in the early and later postsurgical period, the biggest changes of blood flow Doppler parameters were found in the anterior cerebral artery [6]. In children with hydrocephalus, Nishimaki et al. [7] measured RI-ACA and RI-BA. They found out that both indices were significantly increased before drainage procedure, but RI-ACA was more increased than RI-BA. However, indices of both cerebral arteries were significantly increased after drainage procedure, and decrease of RI-ACA was more significant than RI-BA. Significant change of RI-ACA comparing with change of RI-BA before and after drainage procedure is probably determined by anatomical location of the arteries. The anterior artery lies closely to the lateral cerebral ventricles and the third cerebral ventricle, and the basilar artery is located in the basilar cistern in front of the pons. In most of the cases of hydrocephalus, the lateral cerebral ventricles dilate more than the third and the fourth cerebral ventricles. Therefore, the authors of the study assume that dilatation of cerebral ventricles has greater effect on the anterior cerebral ventricle than on the basilar artery [7].

Although the basilar artery does not belong to the arteries with the highest predisposition to early reaction to volume-pressure changes in the intracranial space, assessment of increased RI-BA value and size of the cerebral ventricles, which had been performed in dogs with hydrocephalus, helped to distinguish cases, in which drainage procedure is necessary—with sensitivity of 77% and specificity of 94%. The value of neurological manifestations of symptomatic hydrocephalus correlated with RI-BA value and size of the cerebral ventricles. During measurement of individual dynamics, changes in clinical symptomatology had been accompanied by changes of RI-BA and size of the cerebral ventricles [8].

When observing changes of pulsatility index and cerebral ventricles resistance in children with hydrocephalus before and after drainage procedure, various studies revealed significant increase of PI and RI values of the cerebral ventricles before drainage procedure and significant decrease of PI and RI in functional drainage internal system after surgery. Change of qualitative indices of the Doppler curve was affected by change of Ved. The results of studies showed that increased cerebrovascular resistance before drainage procedure was determined by increased intracranial pressure, which is reversible after drainage procedure. Positive impact of drainage procedure on Doppler parameters of the cerebral arteries is based on postsurgical change of cerebrovascular resistance and regulation of cerebral circulation due to decrease of intracranial pressure [6, 9–12]. Significant relationship between resistance index and pulsatility index of MCA was observed in infants with congenital hydrocephalus before the operation [13].

The assessment of Doppler parameters of cerebral circulation and heart rate variability in preterm neonates with posthemorrhagic hydrocephalus showed that hemodynamic parameters as well as chronotropic regulation of cardiac function changed after drainage procedure [14].

On the contrary, van Bel et al. [15], who investigated ten preterm neonates with posthemorrhagic hydrocephalus before drainage procedure, proved significant increase of PI-ACA resulting from significant increase of Vsyst. After successful performance of drainage procedure, PI-ACA and Vsyst significantly decreased. The values of PI-ACA after drainage of cerebrospinal fluid were within standard range. When van Bel et al. [15] compared values of Ved and Vmean before and after drainage procedure, they did not found any significant changes. It may be concluded that increase of PI-ACA before drainage procedure was determined only by increase of Vsyst [15]. The same results were confirmed by Alvisi et al. [18]. Many researchers claim that increase of Vsyst before drainage procedure is caused by movement and compression of the anterior cerebral arteries through enlarged cerebral ventricles and flow of cerebrospinal fluid into the white matter, which results in decrease of transmural pressure gradient [16–18].

In neonates, infants, and older children, Goh et al. [19, 20] studied relationship between intracranial pressure and resistance index of ACA and MCA. They found good intraindividual correlation between ICP and RI-ACA and RI-MCA in neonates and general good correlation between ICP and RI-ACA and RI-MCA in infants and older children. Difference between the age groups is probably caused by individual pressure-volume compensation of the intracranial pressure in neonates with hydrocephalus in various stages of hydrocephalus and various degree of compliance of the calva and cranial sutures. Intracranial dynamics is more uniform in infants and older children. This corresponds with general good correlation between intracranial pressure and resistance index of the cerebral arteries. Significant decrease of RI-ACA and RI-MCA, determined by increase of Ved, was observed after drainage procedure in all age categories. Only in neonates, increase of Ved was accompanied by moderate increase of Vsyst and Vmean [19, 20].

During continuous observation of blood flow in MCA by transcranial Doppler sonography, positive impact of drainage of cerebrospinal fluid on Doppler parameters of MCA had been observed in children with hydrocephalus during the insertion of ventriculoperitoneal shunt. Insertion of ventricular catheter into the lateral cerebral ventricle with cerebrospinal fluid derivation led to obvious and immediate 30% increase of blood flow in MCA. When drainage procedure had been performed, values of PI-MCA, which were increased before the surgery, returned to standard range. The results of the study confirmed positive impact of cerebrospinal fluid derivation on hemodynamic parameters of cerebral circulation in children with hydrocephalus [21].

Results of various studies emphasize the importance of data from assessment of changes of Doppler parameters of cerebral circulation to the monitoring of *dilatation of cerebral ventricles*. Experiment on newborn rats with progressive communicating hydrocephalus showed that onset of ventricular dilatation was not accompanied by alteration of parameters in the Doppler curve of the cerebral arteries. Pulsatility index of the cerebral arteries had been increased during development of hydrocephalus and followed by progression of ventricular dilatation. This means that dilatation of cerebral ventricles did not change pulsatility index of the cerebral arteries. Instead, the change occurred due to progression of hydrocephalus and increase of

intracranial pressure. It can be concluded that in this developmental stage of hydrocephalus, cerebral circulation was more influenced by increased intracranial pressure than by ventricular dilatation [22]. In chronic stage, changes of cerebral hemodynamics and advanced ventricular dilatation were accompanied by other structural pathological changes [23].

Relation between *dynamics of ventricular dilatation* (progressive, stable, or regressive) and basal and compressive values of RI-ACA was not found in neonates with hydrocephalus before the drainage procedure. It means that dynamics of ventricular dilatation is not the only parameter influencing Doppler parameters of the cerebral arteries. In all cases of neonates with hydrocephalus, intracranial pressure was increased during drainage procedure, and clinical manifestations of intracranial hypertension had diminished after the surgery. Therefore, the authors of the study assume that Doppler parameters of the cerebral arteries are influenced by combination of increased intracranial pressure and ventricular dilatation. Additionally, the results of the study confirmed that not only progressive but also stable ventricular dilatation with increased intracranial pressure has negative effect on cerebral circulation [12]. On the contrary, in neonates with stable ventricular dilatation, in which drainage procedure was not necessary, basal Doppler parameters of blood flow in ACA reached normal values. Similarly, Quinn and Pople [24] confirmed increase of PI-MCA in children with hydrocephalus who experienced dysfunction of drainage system. CT examination, however, revealed change of size of the lateral ventricles only in 10 out of 32 patients. Comparing with stable ventricular dilatation, results showed increased value of PI-MCA and the presence of clinical manifestations of dysfunction of drainage system, in which surgical procedure is necessary. When the procedure had been performed, PI-MCA significantly decreased [24]. However, if intracranial pressure was not increased in stable ventricular dilatation, resistance index of the cerebral ventricles did not change either [25].

Not only increase of intracranial pressure and development of ventricular dilatation but also changes of the cerebral arteries, such as distortion, compression, and stretching may occur in children with hydrocephalus [26].

The results of the study Kolarovszki et al. [12] on children with hydrocephalus confirmed that *asymmetric ventricular dilatation* had significantly influenced values of basal RI-ACA before drainage procedure and compressive RI-ACA after it. Statistical analysis showed that values of basal RI-ACA after drainage procedure and compressive RI-ACA before drainage procedure were not influenced by asymmetric ventricular dilatation. Asymmetric ventricular dilatation before drainage procedure may lead to stretching of the anterior cerebral arteries. When accompanied by increased intracranial pressure, it results in increase of cerebrovascular resistance and RI-ACA value. The presumption that asymmetry of the cerebral ventricle has significant impact on presurgical values of compressive RI-ACA was not confirmed. The authors believe that it was caused by distribution of range of compressive RI-ACA before drainage procedure. In 36 neonates out of 40 (90%), compressive RI-ACA before drainage procedure reached maximal value of 1.0 regardless asymmetric ventricular dilatation. In normal values of intracranial pressure measured after drainage procedure, the values of basal RI-ACA were not influenced by asymmetric ventricular dilatation. In cases with standard values of intracranial pressure in asymmetric ventricular dilatation, dislocation of the anterior cerebral ventricles may occur without

significant stretching and change of cerebrovascular resistance. Compression of the anterior fontanelle in asymmetric ventricular dilatation, which is related to intracranial normotension, may worsen dislocation of the anterior cerebral ventricles if it is accompanied by increase of cerebrovascular resistance resulting in compressive RI-ACA. Based on the study and clinical experience, the authors emphasize the fact that interpretation of Doppler parameters of the cerebral arteries in pediatric hydrocephalus with asymmetry of cerebral ventricles has to be done carefully [12].

In neonates with hydrocephalus, besides hydrocephalus itself, the following pathological changes of the periventricular cerebral tissue may also have negative impact on cerebral circulation: periventricular leukomalacia and peri- and intraventricular hemorrhage.

Impact of these changes on cerebral circulation and Doppler parameters of the cerebral arteries should be taken into consideration when assessing hemodynamic parameters of cerebral circulation in neonates with hydrocephalus in relation to observation of intracranial dynamics and indication of drainage procedure.

In neonates with hydrocephalus, besides hydrocephalus itself, the following pathological changes of the periventricular cerebral tissue may also have negative impact on cerebral circulation: periventricular leukomalacia and peri- and intraventricular hemorrhage. Impact of these changes on cerebral circulation and Doppler parameters of the cerebral arteries should be taken into consideration when assessing hemodynamic parameters of cerebral circulation in neonates with hydrocephalus in relation to observation of intracranial dynamics and indication of drainage procedure.

The most common cause of *periventricular leukomalacia* is perinatal infection (e.g., chorioamnionitis) and hypoxic-ischemic damage of the brain tissue. Considering various degrees of maturity of the brain tissue, consequences of hypoxic-ischemic brain injury differ in preterm neonates and term neonates [27].

In preterm neonates, the periventricular white matter is at higher risk of hypoxia, which leads to focal or diffuse type of periventricular leukomalacia, while in term neonates, it is the white matter near the cerebral cortex, in which cortical or subcortical lesions of white matter can be detected [28].

The cystic leukomalacia lesions do not occur from the moment of primary insult of the brain tissue, but they develop continuously. At first, hyperechogenicity of the periventricular brain tissue is confirmed by a sonography. Then cystic lesions are formed during 10–14 days [29]. Pathological changes of structure of the periventricular brain tissue are accompanied by hemodynamic changes. Dysfunction of cerebral autoregulation was confirmed in preterm neonates with periventricular leukomalacia [30]. Many researchers also confirmed alteration of cerebral circulation in neonates with periventricular leukomalacia. By means of transcranial Doppler ultrasonography, Fukuda et al. observed long-term decrease of blood flow velocity within all major cerebral arteries [31]. In another research on periventricular leukomalacia in neonates with low birth weight, Fukuda et al. confirmed that blood flow in ICA and VA had decreased a few days after birth and then between day 21 and 42 [32]. Research by Ilves et al. [33] revealed that mean velocity of blood flow in ACA, MCA, ICA, and BA had increased in 83 asphyctic term

neonates due to severe hypoxic-ischemic encephalopathy during first days after asphyxia. However, increased mean velocity of blood flow in the cerebral arteries was only short term. During period of 21–59 days, it dropped below standard values of healthy term neonates [33]. Changes of Doppler parameters of MCA in neonates with hypoxic-ischemic encephalopathy were also proven by Liu et al. [34]. In children with severe encephalopathy, the values of RI-MCA were < 0.50 or RI-MCA > 0.90 as a result of change of blood flow velocity in MCA.

To classify *intracranial hemorrhage in neonates*, the grading scale of Papile, which was created in 1978, is still being used [35]. In the past, it was assumed that the grade IV denotes spread of subependymal bleeding into the surrounding brain tissue. Nowadays, decrease of venous drainage and development of venous hemorrhagic infarction are regarded to be the main triggers of intracranial hemorrhage in neonates [27, 36]. Subsequently, porencephalic cysts may develop in the site of periventricular venous infarction. In general, higher grades of intracranial hemorrhage lead to increased risk of severe neurological disorders in children. If degrees III and IV of intracranial hemorrhage occur in active hydrocephalus, the brain tissue and cerebral circulation of a neonate are negatively affected by bleeding itself as well as changes related to intracranial pressure and progressive dilatation of cerebral ventricles. Moreover, there are many extracranial factors, which impact negatively on cerebral circulation, especially in preterm neonates [37–39].

Peri- and intracranial hemorrhage in neonates leads to dysfunction of regulation of cerebral circulation including autoregulation. Increased values of resistance index of the cerebral arteries, which were found out in the site of bleeding, are a sign of increased cerebrovascular resistance and presence of vasoconstriction near hemorrhagic lesions [40, 41]. Various research studies on neonates with posthemorrhagic hydrocephalus showed positive effect of drainage procedures, decrease of intracranial pressure, and the improvement of cerebral circulation.

The issue of frequency and appropriate time management of cerebrospinal fluid derivation during intermittent drainage in neonates with posthemorrhagic hydrocephalus remains open to debate. Large multicentric studies confirmed very low effect of frequent and early performed drainage, based on the assessment of size of the cerebral ventricles, in comparison with a conservative approach [42]. Since one of the prospective goals of intermittent drainage of cerebrospinal fluid is to prevent dysfunction of cerebral circulation due to increased intracranial pressure, changes of Doppler parameters of cerebral circulation in neonates with posthemorrhagic hydrocephalus have become a center of attention.

Nishimaki et al. [43] found out values of RI-ACA in children with posthemorrhagic hydrocephalus were significantly increased before lumbar puncture or puncture of subcutaneous reservoir. But after aspiration of 5–10 ml/kg, they significantly decreased [43]. Similarly, Kempley and Gamsu [44] confirmed decrease of intracranial pressure accompanied by significant increase of Vmean and decrease of PI-ACA, when cerebrospinal fluid derivation had been performed in newborn with posthemorrhagic hydrocephalus. Quinn et al. [45] compared impact of increased intracranial pressure and cerebrospinal fluid derivation on blood flow in ACA and ICV in neonates with posthemorrhagic hydrocephalus. RI-ACA was significantly increased before drainage procedure. But afterward, it decreased significantly. Changes of blood flow velocity in ACA were not accompanied by change of blood flow velocity in ICV [45].

Maertzdorf et al. [46] observed hemodynamic parameters of ACA and MCA in the Doppler curve of preterm neonates with intraventricular hemorrhage and posthemorrhagic hydrocephalus during early gestation weeks. Aspirations of cerebrospinal fluid from subcutaneous reservoir of the ventricular catheter (type Ommaya) had been performed repetitively. When ICP before drainage procedure was ≥6 cm H_2O, then Ved and Vmean had increased significantly after performing aspiration. When ICP was <6 cm H_2O, RI-ACA and RI-MCA had decreased. Value of Vsyst was significantly changing after cerebrospinal aspiration. The results confirmed good intraindividual correlation between RI-ACA, RI-MCA, and ICP in neonates with posthemorrhagic hydrocephalus [46]. The use of near-infrared spectroscopy revealed that cerebrospinal fluid derivation from subcutaneous reservoir lead not only to change of Doppler parameters of cerebral circulation, especially significant decrease of pulsatility index, but also to improvement of intravascular oxygenation of cerebral circulation [47, 48].

During assessment of effect of periventricular posthemorrhagic lesions on Doppler parameters of blood flow in ACA of neonates with hydrocephalus, significant correlation had been found between periventricular posthemorrhagic lesions and basal RI-ACA and compressive RI-ACA after drainage procedure. Before drainage procedure, Doppler parameters in ACA were influenced by increased intracranial pressure and posthemorrhagic lesions [12].

Based on the research, it can be concluded that cerebrospinal fluid derivation in neonates with posthemorrhagic hydrocephalus leads to improvement of cerebral blood flow. While indicating and planning derivation of cerebrospinal fluid, changes of Doppler parameters of cerebral circulation should be taken into account [1] (**Figure 1**).

Changes of Doppler parameters of the cerebral arteries were found also in cases with *dysfunction of drainage system* after surgical revision in children with hydrocephalus.

Pople [49] focused on identification of referential values of PI-MCA in children with hydrocephalus with functional internal drainage system (**Table 1**). The sample included 248 asymptomatic children with hydrocephalus with functional shunt system. They were 1 week to 16 years old. It is known that blood flow velocity in the cerebral arteries increases during aging. Changes of blood flow velocity in the cerebral arteries are more variable in children, especially in younger age groups, than in adults. The highest blood flow velocity was measured between 3 and 4 years of age. Since then it had been gradually decreasing to the level of values in adults. Pulsatility index had been significantly decreasing during the first 6 months of age. The lowest value was measured between 2 and 6 years of age. Since then it had been gradually increasing up to the value of 0.9 in the age of 16. In addition to identification of referential values of PI-MCA in children with hydrocephalus with functional internal drainage system, Pople emphasized significant interindividual differences of Doppler parameters and importance of following the intraindividual trend [49]. In 63 children with hydrocephalus with dysfunction of drainage system, values of PI-MCA were compared with referential values. It was found out that increase of PI-MCA determines shunt malfunction with sensitivity of 56% and specificity of 97%. The values of PI-MCA correlated with intracranial pressure of children with shunt obstruction [50]. Increased resistance index of the cerebral arteries was also confirmed in children with dysfunction of drainage systems [12, 51] (**Figure 2**).
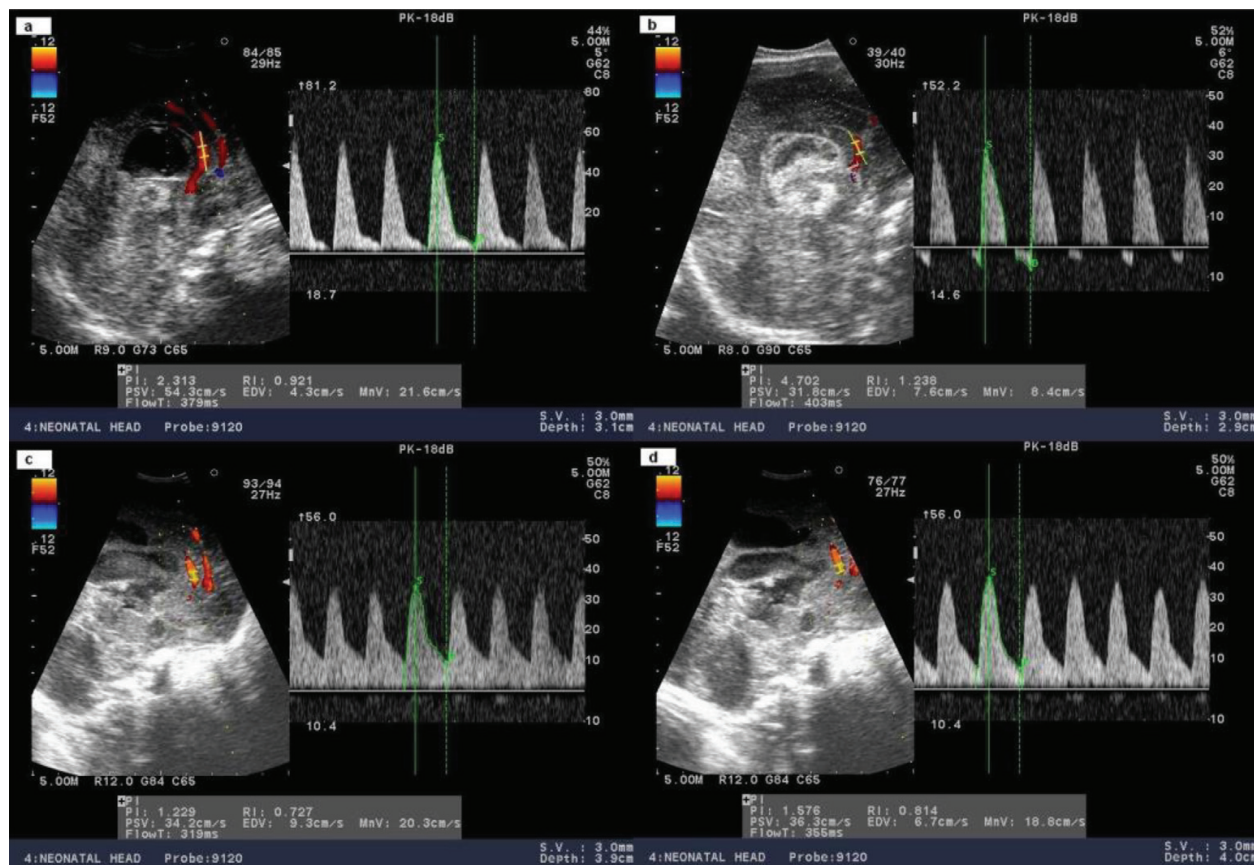
Figure 1. Doppler parameters of blood flow in the arteria cerebri anterior in the preterm neonate with posthemorrhagic hydrocephalus before and after drainage procedure. (a) Basal parameters before drainage procedure (increased RI, decreased Ved), (b) positive compressive test of the anterior fontanelle before drainage procedure (reverse blood flow during diastole), (c) basal parameters after drainage procedure (normal values of RI and Ved), and (d) negative compressive test of the anterior fontanelle after drainage procedure. Abbreviations used in the picture: RI, resistance index; Ved, end-diastolic velocity of blood flow; Vsyst, maximal systolic velocity of blood flow; PI, pulsatility index; Vmean, mean velocity of blood flow (figure—author).

Age	Vsyst (cm/s) (mean)	Ved (cm/s) (mean)	Vmean (cm/s) (mean)	Pulsatility index (mean)	Number (n = 248)
0–3 months	19–107 (63)	3–43 (23)	8–64 (36)	0.83–1.62 (1.23)	16
4–6 months	40–124 (82)	18–50 (34)	25–73 (49)	0.77–1.26 (1.01)	11
7–12 months	25–165 (95)	7–71 (39)	14–110 (62)	0.67–1.20 (0.94)	15
1–2 years	58–166 (112)	28–84 (56)	47–113 (75)	0.66–1.02 (0.82)	26
2–6 years	62–170 (116)	28–92 (60)	42–122 (82)	0.48–0.99 (0.74)	77
6–10 years	47–155 (101)	23–79 (51)	37–107 (67)	0.55–1.00 (0.77)	61
10–16 years	37–153 (95)	20–72 (56)	24–96 (60)	0.59–1.22 (0.89)	42

Table 1. Referential values of PI-MCA in children with hydrocephalus with functional internal drainage system [49].

Figure 2. Dysfunction of ventriculoperitoneal shunt in the child with hydrocephalus. Manifestation of fistula and subcutaneous cerebrospinal fluid accumulation. CT image shows the dislocation of ventricular catheter from the intracranial space, fistula, and subcutaneous cerebrospinal fluid accumulation (figure—author).

Assessment of cerebral circulation by transcranial Doppler sonography can be used not only to observed functions of shunts but also ventriculostomy of the third cerebral ventricle. Vajda et al. [52] found out that PI-MCA significantly decreased in children with obstructive hydrocephalus after successful ETV. The difference was not statistically significant when they compared PI-MCA measured immediately after ETV with value measured in the fifth day after surgery. Effect of ventriculostomy was confirmed by assessment of cerebrospinal fluid flow using cine-phase MRI examination. Clinical symptomatology improved immediately after the procedure in 17 out of 22 patients. No correlation between PI-MCA and age or gender of children in the sample of patients was found. The results showed importance of Doppler sonography for observation of ETV functioning in the early postsurgical period [52].

In addition to increased resistance index of the cerebral arteries, vascular reactivity malfunction to p_aCO_2 change was detected in children with active hydrocephalus before drainage system insertion and in dysfunction of drainage system. When drainage system was inserted and dysfunctional shunt revised, resistance index decreased significantly. Then cerebrovascular reactivity to p_aCO_2 change had been improved and that also led to functional cerebral circulation and regulation change [53].

Taylor et al. [54] used *compressive test on the anterior fontanelle* during transcranial Doppler sonography examination in children with abnormal intracranial compliance. They studied basal values of RI-ACA and change of RI-ACA during the compressive test (**Figure 3**). The change was expressed as percentage difference in contrast to basal value. The basal values of RI-ACA of preterm neonates and neonates with abnormal intracranial compliance were significantly increased when compared to basal values of healthy term neonates. Only slight change of RI-MCA was observed in healthy preterm neonates and healthy term neonates during compression on the anterior fontanelle. However, RI-MCA was significantly increased in neonates with abnormal intracranial compliance. Basal values of RI-MCA were increased in neonates with increased intracranial pressure. Hemodynamic reaction of the cerebral vessels to compression of the anterior fontanelle had improved after drainage of cerebrospinal fluid. Compression test on the anterior fontanelle during transcranial Doppler sonography examination can help to detect alteration of intracranial compliance before increase of intracranial pressure. This is manifested
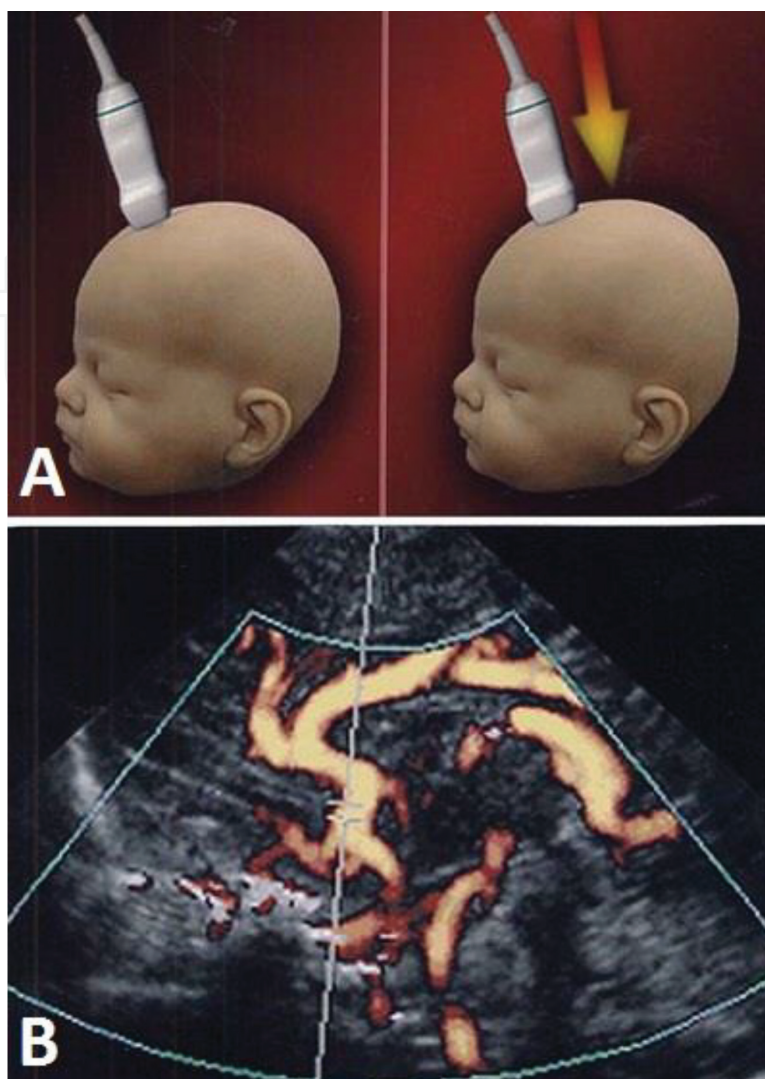
Figure 3. The compression test on the anterior fontanelle. (A) Compression by the sonographic probe and (B) the Doppler curve of the anterior cerebral artery [53].

by increased basal values of resistance index. The study showed possibility of indirect noninvasive measurement of intracranial compliance and intracranial pressure by transcranial Doppler sonography [54]. In another study, Taylor et al. [36] assessed hemodynamic reaction of the anterior cerebral artery during compressive test on the anterior fontanelle in neonates with hydrocephalus. The research was performed by means of compressive test. It revealed significant increase of RI-ACA in neonates who were indicated for drainage procedure and in which increased intracranial pressure was confirmed by direct measurement [36].

Westra et al. [55] also dealt with the use of compressive test on the anterior fontanelle in children with hydrocephalus. They confirmed significantly increased basal and also compressive values of RI-ACA in children hydrocephalus with increased intracranial pressure. Significant decrease of basal and compressive values of RI-ACA was found out when drainage procedure had been performed. Based on the results, they defined the boundary value of 0.70 for basal RI-ACA and 0.90 for compressive RI-ACA [55].

Gera et al. [56] focused on assessment of Doppler parameters of the anterior cerebral artery in relation to drainage procedure indication and change of measured Doppler parameters after drainage procedure. In children indicated for drainage procedure, they found out significantly increased value of basal RI-ACA and RI-ACA during compressive test. But after drainage procedure, the value of basal RI-ACA and compressive RI-ACA significantly decreased [56].

Change of Doppler parameters indicates increase of intracranial compliance after drainage procedure. However, no correlation between ICP and RI-ACA (both basal and compressive) was found. The researchers believe that it is caused by complexity of the relationship between ICP and RI and potential nonlinearity of the relationship. During observation of RI-ACA in children with hydrocephalus in relation to indication of drainage procedure, the following values of basal RI-ACA were found out: sensitivity of 72.5%, specificity of 80%, and diagnostic accuracy of 75%. Assessment of RI-ACA by compressive test on the anterior fontanelle showed sensitivity of 75%, specificity of 100%, and diagnostic accuracy of 83.3%. False negativity in assessment of basal and compressive RI-ACA was the same (25%). **Table 2** presents comparison of the role of assessment of hemodynamic parameters of the cerebral arteries by Doppler sonography during compressive test in children with hydrocephalus and indication of drainage system.

The compressive test on the anterior fontanelle increases sensitivity and specificity of resistance index and pulsatility index in regard to indirect measurement of increased intracranial pressure and decreased intracranial compliance in children with hydrocephalus. On the other hand, results of the compressive test require more careful assessment of effect of intra- and extracranial factors on cerebral circulation because their influence on compressive values is more significant than effect on basal values. Pressure applied to the anterior fontanelle during compressive test is defined within the range 0–200 g/cm^2. The pressure can gradually increase when using an ophtalmodynamometer [54]. When using a sonographic probe, shape (linear or convex) and size of a probe and pressure, which will be created by a doctor, need to be taken into consideration. Therefore, if a child was indicated for sonographic examination, it should be performed by the same doctor and the same probe. Regarding indirect measurement of intracranial hypertension and intracranial compliance, false positivity of compressive test can be found in preterm neonates who require intensive care (instability of extracranial factors), in severe stages of intra- and periventricular hemorrhage and ventricular dilatation. False negativity of compressive test can be caused by liquorea, subcutaneous cerebrospinal fluid fistula, or small size of the anterior fontanelle [12].

Although transcranial Doppler sonography has been used more than 30 years to assess Doppler parameters of cerebral circulation, interpretation of parameters in the Doppler curve of the

	Taylor [57] (%)	Westra et al. [55] (%)	Gera et al. [56] (%)
Sensitivity	45	81	75
Specificity	95	100	100

Table 2. The role of assessment of hemodynamic parameters of the cerebral arteries by Doppler sonography during compressive test in children with hydrocephalus and indication of drainage system.

cerebral arteries, intracranial pressure, intracranial compliance, and cerebral hemodynamics in children with hydrocephalus remains to be an open topic. On the one side, results of various studies showed possibility of indirect noninvasive assessment of intracranial pressure and compliance by means of transcranial Doppler sonography. On the other hand, results showed limitations and difficulties when assessing Doppler parameters of cerebral circulation in children with hydrocephalus. When assessing relation between intracranial pressure, resistance index, and pulsatility index of the cerebral vessels, wide range of factors, which can change shape and properties of the Doppler curve, need to be taken into consideration. Behrens et al. [58] used a mathematical model of cerebrospinal fluid circulation, which confirmed that relation between ICP and PI-MCA is significantly influenced by vascular compliance, autoregulation, and arterial pressure. They believe that individual variability of these physiological parameters is responsible for inaccurate reference of ICP value [58]. Similarly, Hanlo et al. [59] confirmed decreased resistance index and pulsatility index of the cerebral vessels measured in children with progressive hydrocephalus after drainage procedure. However, during longitudinal simultaneous ICP/transcranial Doppler sonography monitoring, correlation between ICP, RI, and PI was very weak. Based on the results, which showed wide range of referential Doppler parameters of cerebral circulation and impact of extracranial factors, authors of this study believe that pulsatility index and resistance index of the cerebral vessels do not help in assessment of intracranial dynamics in patients with increased intracranial pressure [59].

This inconsistency of results on assessment of relationship between RI and PI of the cerebral vessels, and intracranial pressure has led to research of more accurate noninvasive parameters of intracranial pressure. Hanlo et al. [59] presented new Doppler index known as trans-systolic time. The results confirmed that trans-systolic time of the cerebral arteries in the Doppler curve is less influenced by other factors (e.g., heart rate) and is more accurate for comparison of ICP, RI, and PI changes [60]. Also, Leliefeld et al. [61] confirmed significant correlation between trans-systolic time and ICP. Despite these positive results, assessments of trans-systolic time of the cerebral arteries are not used for noninvasive measurement of intracranial pressure. It might be caused by a lack of referential range in children population and lack of experience with use in clinical practice [61]. In another study, Leliefeld et al. [62] dealt with possibility to use MRI examination of cerebral circulation for indirect measurement of intracranial pressure. They found out that standard values of blood flow velocity in the brain and low values in ADC map were referred to compensated hydrocephalus without a need of drainage procedure. They claim that noninvasive changes of cerebral circulation by MRI examination enable to distinguish the cases of compensated children with hydrocephalus with standard intracranial pressure without a need of drainage procedure from the cases of gradually progressive hydrocephalus with a need of drainage surgery [62].

Galarza and Lazareff [63] focused on clinical validity of transcranial Doppler sonography in children with various types of hydrocephalus. The study showed that values of PI-MCA and RI-MCA were significantly higher in progressive hydrocephalus with a need of drainage procedure. On the other hand, RI-MCA and PI-MCA were not increased, and blood flow velocity in MCA was not decreased in the cases with compensated hydrocephalus (also known as arrested hydrocephalus) and ventriculomegaly (or essential ventriculomegaly). The results

showed importance of transcranial Doppler sonography for indication of drainage procedure in children with hydrocephalus. However, the authors emphasize the importance of individual and careful assessment of Doppler parameters of cerebral circulation regarding children hydrocephalus in clinical practice [63].

Rodríguez-Nuñez et al. [64] confirmed the role of clinical manifestations of intracranial hypertension, radiological morphometric parameters of the brain (Evans' index), biochemical parameters of cerebrospinal fluid (level of hypoxanthine, xanthine, and urea acid), and Doppler parameters of the cerebral circulation during assessment of children hydrocephalus and indication of drainage procedure [64].

Based on the results of the works of several authors, it seems that *optic nerve sheath diameter (ONSD) ultrasonography* could be a good noninvasive method for the indirect detection of raised intracranial pressure [65–68].

The study of Ragauskas et al. [69] compared the diagnostic reliability of optic nerve sheath diameter ultrasonography with a transcranial Doppler sonography and the absolute values of intracranial pressure in neurological patients. The authors of this study found that the noninvasive ICP measurement method based on two-depth transcranial Doppler technology has a better diagnostic reliability on neurological patients than the ONSD method when expressed by the sensitivity and specificity for detecting elevated ICP >14.7 mmHg [69]. Tarzamni et al. [70] analyzed the diagnostic accuracy of ultrasonographic ONSD measurement and color Doppler indices of the ophthalmic arteries in detecting elevated intracranial pressure. While the ultrasonographic mean binocular ONSD was completely accurate in detecting elevated ICP, color Doppler indices of the ophthalmic arteries were of limited value [70].

Based on the recent literature, it seems to be a good idea to use sonographic methods, optic nerve sheath diameter ultrasonography and transcranial Doppler sonography for the noninvasive detection of intracranial hypertension. Further research for the application in clinical practice in pediatric hydrocephalus is needed.

3. Conclusion

Based on the clinical experience and scientific research on pediatric hydrocephalus, we can summarize the role of transcranial Doppler sonography in assessment of cerebral circulation and intracranial dynamics of pediatric hydrocephalus as follows:

1. Assessment of Doppler parameters of cerebral circulation before drainage procedure in children with hydrocephalus revealed alteration of cerebral circulation which is potentially reversible. Doppler sonography showed the improvement of cerebral circulation after the drainage procedure in pediatric hydrocephalus.

2. Results of compressive test on the anterior fontanelle increase validity of assessment of cerebral circulation by transcranial Doppler sonography and enable indirect assessment of decrease of intracranial compliance. Increase of basal Doppler parameters shows increase of intracranial pressure.

3. While interpreting Doppler parameters of cerebral circulation measured in a child with hydrocephalus, it is important to assess impact of both intra- and extracranial factors on cerebral circulation. Then it is possible to say to which extent Doppler parameters show the real value of intracranial pressure and intracranial compliance. The results showed that asymmetric dilatation of the lateral cerebral ventricles and posthemorrhagic periventricular lesions influence Doppler parameters of cerebral arteries both in intracranial hypertension and normotension.

4. The results show that the Doppler parameters of cerebral arteries in active hydrocephalus are not increased due to dilatation of cerebral ventricles but increased intracranial pressure.

5. Assessment of Doppler parameters of blood flow in cerebral arteries in children with hydrocephalus with functional drainage system or ETV revealed standard range of values. On the other hand, the values of Doppler parameters increased in the shunt-dependent children with dysfunctional drainage system or ETV, even though the cerebral ventricles enlarged slightly or maintained the same size. After successful revision surgery, the value of Doppler parameters dropped down to standard range.

6. Assessment of cerebral circulation by transcranial Doppler sonography in children with hydrocephalus can be easily performed by an accessible, indirect, noninvasive, bedside, and repetitive measurement of intracranial pressure and intracranial compliance. Regarding complexity of intracranial dynamics, relationship between intracranial pressure and Doppler parameters of the cerebral arteries, individual assessment of measured Doppler parameters, as well as assessment of effect of extra- and intracranial factors to cerebral circulation should be performed in each case of pediatric hydrocephalus. If the results are not clear, examination should be repeated, and intraindividual tendency should be observed in the child. It is important to design and follow detailed methodology of sonographic examination and include it into the report of assessment of intracranial dynamics in the child with hydrocephalus.

7. Clinical applications of transcranial Doppler sonography in pediatric hydrocephalus are as follows:

   • Indication and timing of drainage procedure;

   • Monitoring of effectivity of drainage procedure—internal drainage systems (shunts), ETV, external ventricular drainage, and cerebrospinal fluid derivation from subcutaneous reservoir (determination of frequency and amount of aspired cerebrospinal fluid);

   • Monitoring of function and detection of malfunction of external and internal drainage systems and ETV;

   • Assessment of the dependence of the child on drainage system (shunt-dependence)—important for indication of external ventricular drainage or subcutaneous reservoir conversion on internal drainage system (shunt) or ETV, need for a revision of dysfunctional drainage system.

To sum up, it can be said that including assessment of cerebral circulation by transcranial Doppler sonography into management of child with hydrocephalus provides additional

information to clinical manifestations and morphological results of imaging studies. This helps better understand intracranial dynamics and activity of hydrocephalus in regard to indication and timing of drainage procedure.

Acknowledgements

Abbreviations

ACA	anterior cerebral artery
BA	basilar artery
ICA	internal carotid artery
ICP	intracranial pressure
ICV	internal cerebral vein
MCA	middle cerebral artery
ONSD	optic nerve sheath diameter
PI	pulsatility index
RI	resistance index
VA	vertebral artery
Ved	end-diastolic blood flow velocity
Vmean	mean blood flow velocity
Vsyst	maximal systolic blood flow velocity

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