Valproic acid (VPA) is a well-known antiepileptic drug with significant teratogenic effect when administered during pregnancy. To investigate the transplacental transport of VPA, we used an in vitro experiment of dual perfusion of a human placental cotyledon. Eighteen normal placentas at term were investigated; ten were treated with a therapeutic dose of VPA (initial level at maternal circulation 75 μg/ml), while the remaining eight were supplied with toxic VPA doses (initial level at maternal circulation 225 μg/ml). VPA concentrations in fetal compartment were lower than those in the maternal compartment at all timepoints with both doses applied. The maternal and foetal VPA concentrations were stable at 60 min and 120 min for the therapeutic dose of VPA (transfer percentages from the maternal to the fetal circulation were 22.7 ± 9.1% and 22.7 ± 7.1%, respectively). Interestingly, a significant decrease of VPA level in the maternal perfusate was observed after 120 min due to the slightly higher transfer of the drug to the foetal compartment. In conclusion, our data confirmed an easy and rapid transfer of VPA across the placental barrier. Since the incidence of congenital malformations in infants correlates positively with VPA concentrations in maternal serum, monitoring of VPA should be mandatory due to possible harmful effects on the foetus.

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of women at childbearing age with epilepsy and psychiatric disorders treated with VPA is on the increase [20, 29]. Nowadays, epilepsy affects 0.5% of pregnant women, thus being the most common neurological disorder in this group [35].

Despite the inevitable harmful effects on the foetus, treatment with antiepileptic drugs (AEDs) cannot be discontinued in pregnant woman with epilepsy since uncontrolled seizures per se may cause foetal distress or even miscarriage [31]. Thus, the benefits of the antiepileptic treatment clearly predominate the possible disadvantages. To improve the safety of the therapy for epilepsy in pregnancy, it is necessary to explain all the aspects of pharmacokinetics of AEDs in relation either to the mother or the foetus. A crucial event determining the foetal exposure to the maternal drug is its ability to pass across the placenta. However, for ethical reasons and methodological limitations, studies assessing this process could not be performed in vivo. Due to interspecies variations, the results from animal studies can not be directly extrapolated to humans. Therefore, several experimental methods in vitro have been developed to investigate this aspect regarding drugs and toxins [9, 23, 30, 36]. Currently, we investigated the VPA transfer across the placenta, applying the experimental model of dual perfusion of a single human placental cotyledon.

**MATERIALS AND METHODS**

The current study was carried out on an experimental model of the dual recirculating perfusion system for an isolated placental lobule, originally described by Schneider et al. [37], with slight modifications by Miller et al. [22]. The study was approved by the Ethics Committee of Medical University of Lublin and written consent obtained from all participant patients. Altogether, eighteen term placentas were collected from healthy women who have had uncomplicated pregnancies at the Department of Obstetrics and Pathology of Pregnancy, Medical University of Lublin, Poland, from 2006–2007. Placentas were immediately submitted to the laboratory to perform the perfusion of the suitable placental lobule within 7–10 minutes after birth. The “foetal and maternal circuits” were established by cannulation of the foetal artery and vein, as well as by the placement of two needles into the intervillous space. The lobule was placed in a plexiglass perfusion chamber filled with buffered Krebs solution (500 ml 0.9% NaCl and 70.3 mg Na₂HPO₄), the composition of which resembles that of amniotic fluid. The foetal (100 ml) and maternal (250 ml) circuits were perfused with a fluid based upon tissue medium (Medium 199 W/HBSS, Life Technologies, Paisley, Scotland). Both circuits were maintained by peristaltic pumps. The foetal and the maternal flow rates were set at 3.8 ± 0.1 ml/min and 14 ml/min, respectively. The maternal perfusate was equilibrated with the mixture of carbogene (95% O₂ and 5% CO₂) and the foetal perfusate was gassed with 95% N₂ and 5% CO₂. The created gas terms outlined above gave conditions close to those found in umbilical arteries in vivo.

The temperature of both the reservoirs and inside the perfusion chamber was kept at 37°C, and pH of perfusate was maintained between 7.2–7.4. Each perfusion lasted 150 min and the first 30 min was considered as an adaptation period. The physical integrity and the function of each lobule was monitored (foetal arterial pressure ≤ 60 mm Hg, foetal to maternal leakage of perfusate ≤ 2 ml/hr, foetal artery to vein oxygen gradient ≥ 90 mm Hg), according to Cannell et al. [6].

The experiment was performed in two groups: A and B. Group A included perfusions of 10 placental lobules, when a therapeutic dose of VPA (Depakine I.V., Sanofi Biocom, Warsaw, Poland) was added to the maternal circuit resulting in the final concentration of 75 μg/ml. This dose corresponds with an accepted therapeutic concentration of VPA in human plasma ranging from 40–100 μg/ml [6]. To test the saturability of transfer, eight placental lobules (group B) were perfused with 3-fold higher concentration of VPA (toxic dose) amounting to 225 μg/ml at the maternal circuit. During the study, the samples of perfusate from both maternal and foetal circuits were checked for VPA concentration every 60 min. The samples were subsequently centrifuged and stored at -20°C, until determinations were performed. The concentration of VPA was measured by immunofluorescent method (Abbott Laboratories, Abbott Park, IL, USA). The transfer percentage of the drug from maternal to foetal circulation was calculated using the following equation:

\[
100 \times \frac{C_f \times V_f}{(C_f \times V_f) + (C_m \times V_m)}
\]

where \(C_f\) is the foetal concentration of the drug, \(V_f\) is foetal perfusate volume, \(C_m\) is the maternal concentration of the drug, and \(V_m\) is the maternal perfusate volume [13].

Statistical analysis was performed by the non-parametric Mann-Whitney U test since values of quantitative variables did not show the normal distribution in the Shapiro-Wilk test. The statistical package used was SPSS-software package (version 14.0 PL for Windows; SPSS Inc., Chicago, IL, USA); p value less than 0.05 was considered statistically significant.

**RESULTS**

In group A, the VPA concentration in the maternal circuit after 60 and 120 min of the experiment were 30.8 ± 10.8 μg/ml and 30.2 ± 8.5 μg/ml (p = NS), respectively. VPA concentrations in the foetal circuit were 24.9 ± 9.9 μg/ml and 25.5 ± 6.5 μg/ml (p = NS), respectively (after 60 and 120 min). Concentrations of VPA in foetal circuit at both time-points were significantly lower than those in the maternal circuit, amounting to 81.3% and 84.3%. In group B, 60 and 120 min after the addition of VPA, concentrations of the drug in the maternal circuit were 97.4 ± 37.0 μg/ml and 83.5 ± 23.6 μg/ml.
Table 1. VPA transfer percentage (±SD) after the administration of therapeutic (group A) and toxic (group B) dose of VPA to the maternal perfusate.

<table>
<thead>
<tr>
<th>Group</th>
<th>Timepoints (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td>A (n = 10)</td>
<td>22.7 ± 9.1</td>
</tr>
<tr>
<td>B (n = 8)</td>
<td>21.9 ± 5.6</td>
</tr>
</tbody>
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(\(p < 0.05\)), respectively, whereas these concentrations in the foetal circuit were 74.8 ± 13.0 \(\mu\)g/ml and 81.0 ± 16.1 \(\mu\)g/ml \((p = \text{NS})\), respectively (Fig. 1B). Similarly to group A, the concentration of VPA in the foetal circuit at 60 min was significantly lower than that in the maternal circuit, amounting to 76.8%, whereas at 120 min the concentration of the drug in the foetal circuit displayed a similar value (97%) to that at the maternal circuit.

The transfer percentage of VPA from the maternal to the foetal reservoir at 60 min was similar with both concentrations applied (22.7 ± 9.1% with 75 \(\mu\)g/ml and 21.9 ± 5.6% with 225 \(\mu\)g/ml).

There were no significant differences in VPA transfer percentage after 120 min of the experiment when different drug doses were compared (22.7 ± 7.1% with 75 \(\mu\)g/ml and 23.9 ± 5.3% with 225 \(\mu\)g/ml) (Tab. 1).

**DISCUSSION**

A limited number of studies elucidated the mechanisms of VPA transport across the human placenta but their results are conflicting [4, 5, 10, 11, 14, 16, 17]. Initial information was based on the measurement of the VPA concentration ratio between cord and maternal serum at the time of delivery. In this indirect method, it was found that VPA crosses the placenta and reaches the foetus, at least at the later part of pregnancy. Although a previous report suggested a lower concentration of VPA in the cord blood than in maternal serum (ratio 0.1–0.5) [5], further studies showed reverse tendencies [4, 10, 14, 16, 17]. They revealed that the VPA level in foetal (cord) serum was equal or exceeded that in the maternal serum (ratio 1–3) in the majority of cases. This phenomenon was also found in a pregnant Rhesus monkey treated with VPA [10]. In contrast, the average steady-state foetal/maternal unbound VPA plasma concentration ratio was 0.81 ± 0.09 during maternal drug administration in pregnant sheep [21]. However, these results could be influenced by the fact that this experiment was performed 1–2 weeks before term [21].

Previous data indicated a high degree of foetal exposure to VPA after its administration to the gravida. Furthermore, it was shown that the mean half-life of VPA in neonates of epileptic mothers was several times longer than those in adults, 47 ± 15 hr and 8–17 hr, respectively [12, 17, 28]. Although in vivo studies revealed the fact of rapid transfer of VPA across the placental barrier, only in vitro experiments were able to provide more precise data. Currently, we used the dual recirculation human placental system and confirmed a rapid transplacental passage of VPA. We found that for the therapeutic dose of VPA, the system was in an equilibrium state, i.e. maternal and foetal VPA concentrations were stable after one and two hours of the experiment. However, we observed a significant decrease of the VPA level in maternal perfusate at 2 hr due to a slightly higher transfer into the foetal compartment. This was generally consistent with the results by Fowler et al. and Barzago et al. who also did not find any accumulation of the drug in placental tissue [4, 11].

In contrast to in vivo studies, in our and other in vitro experiments [4, 11], VPA concentrations in the foetal compartment were lower than in the maternal compartment at all timepoints, and with different concentrations applied. This phenomenon could be explained by a higher binding of VPA to the foetal than to the maternal protein, especially during the last few weeks of pregnancy [26]. The reduction of maternal plasma protein binding of VPA was probably aggravated by the increased plasma free acids level at this period [26, 27]. A similar diversity between results of in vivo and in vitro studies was found recently for diazepam metabolism [24].

Only a few data explain the mechanism by which VPA crosses through the biological membranes, and the detailed mechanisms of the transplacental passage of VPA are still
unknown. The animal model suggested that VPA passes the placental barrier via passive diffusion, as with most chemical agents [21]. However, VPA as a low-molecular weight (144 Da) fatty acid with pKa of 4.9 is almost completely ionized at physiological pH that may theoretically alter its placental permeability [7, 34]. Recently, it was shown that the transplacental passage of VPA may be mediated by a proton-linked saturable transport system, including the family of monocarboxylic acid transporters (MCT). The action of this system could facilitate the transplacental transport of VPA and additionally increase its foetal concentration [25].

It was confirmed that the incidence of congenital malformations in infants correlates positively with VPA concentrations in maternal serum [15, 19]. Therefore, all efforts should be undertaken to reduce foetal exposure to this drug. One option could be a reduction of the placental drug transfer. In fact, Barzago et al. showed that this is possible by encapsulation of VPA in liposomes which serve as drug carriers [4]. However, it should be proved whether such a modification does not influence the anticonvulsant activity of VPA before it becomes a routine therapeutic option. To date, the prescription of the lowest effective dose of VPA is recommended, and divided into 2–3 doses. Additionally, a close monitoring of maternal serum drug level is mandatory to avoid its dangerous peak concentration [18].

Despite the introduction of several new AEDs in recent decades, no agreement has been reached about the safest AED in relation to pregnancy; all of them cross the placenta, at least to some extent [23, 29]. Therefore, further studies are needed to improve the safety of antiepileptic therapy in pregnancy. There is no doubt that the placental perfusion method will be helpful in this respect.

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