Progesterone supplementation extends uterine receptivity for blastocyst implantation in mice

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Abstract

We previously showed that blastocyst can initiate implantation beyond the normal ‘window’ of uterine receptivity on day 5 of pregnancy and pseudopregnancy (PSP) in mice. In this study, we investigated whether uterine receptivity for blastocyst implantation can be further extended on day 6 of PSP and the role of progesterone (P4) on this event. Embryo transfers, experimentally induced decidualization, in situ hybridization and [3H]thymidine incorporation were performed. Blastocysts initiate attachment reaction within 48 h when transferred on day 5, but not on day 6 of PSP. Likewise, decidualization reaction occurred on days 4 and 5 of PSP, but completely failed on day 6. However, P4 supplementation partially retains uterine receptivity for blastocyst implantation and decidualization on day 6 of PSP. In addition, certain indicators of uterine receptivity, such as cell proliferation profile and expression patterns of implantation-related genes were similarly observed on days 4 and 5 of PSP, but not on day 6. Consistent with embryo transfer and decidualization, exogenous administration of P4 partially restores these indicators on day 6 of PSP. We concluded that critical physiological changes occur between days 4 and 5 of PSP, leading to uterine non-receptivity on day 6, but P4 is able to extend the uterine receptivity through day 6.


Introduction

Uterine milieu for blastocyst implantation is classified into prereceptive, receptive, and non-receptive phases. Uterine receptivity is defined as the window of limited time, when the uterine environment is conducive to support blastocyst growth, attachment reaction, and subsequent events of implantation (Psychoyos 1973, Paria et al. 1993, Dey 1996). Extensive embryo transfer experiments were performed on various days of pseudopregnancy (PSP), and the first sign of attachment reaction in the implantation process, the increased vascular permeability, was examined 24 h after embryo transfer to understand uterine receptivity in mice. These experiments suggested that blastocyst can implant only for a limited period on day 4 of pregnancy or PSP. The establishment of uterine receptivity for blastocyst implantation in rodents depends on an appropriate combination of P4 and estrogen, but the molecular events by which estrogen converts the P4-primed uterus to the receptive state, activates the blastocyst, and initiates the implantation process remain ill-defined.

We have previously shown that the ‘window’ of uterine receptivity for blastocyst implantation in mice remains open for an extended period at lower estrogen (E2) levels (3 ng) but rapidly closes at higher levels (Ma et al. 2003). Rapid closure of uterine receptivity at high E2 levels is accompanied by aberrant expression of implantation-related genes. These results demonstrate that optimal levels of ovarian steroids are critical in regulating molecular mechanisms for uterine receptivity in mice. This study utilized delayed implantation model where recipient mice for embryo transfer were ovariectomized and treated with exogenous hormones to monitor implantation rates under various experimental conditions. Thus, one question remains to be answered is whether the ‘window’ of uterine receptivity can be extended in mice with or without hormonal manipulation.
Cytosolic phospholipase A₂ (cPLA₂) is a fatty acid liberating enzyme which sits upstream of cyclooxygenases in prostaglandin (PG) biosynthetic pathway (Murakami et al. 2000). Consistent with critical roles of PGs in implantation and decidualization (Lim et al. 1997), cPLA₂-deficient female mice also exhibit uterine defects (Song et al. 2002). During analysis of implantation phenotypes in these mice, we found that blastocysts which failed to initiate the attachment reaction during the expected time show implantation one day later on day 6 of pregnancy (Song et al. 2002). This suggested that blastocysts require longer time to initiate the implantation process under the condition of sub-optimal uterine receptivity such as uteri deficient of cPLA₂ with lower levels of PGs at the time of implantation. Further investigation with extensive embryo transfers using normal recipients on day 5 of PSP demonstrated that blastocyst can initiate the implantation process in conventionally referred non-receptive uterus (Song et al. 2002).

These findings led us to revisit the definition of ‘window’ of implantation with extensive embryo transfer on extended days of PSP and investigate the role of progesterone in retaining uterine receptivity in mice. We show here that blastocyst can implant on day 5, but not on day 6 of PSP and that P₄ supplementation partially extends uterine receptivity for blastocyst implantation on day 6 of PSP possibly by conditioning uterine environment for implantation via modulation of uterine cell proliferation and expression of some implantation-related genes.

Materials and Methods

Mice

Adult female mice were mated with fertile or vasectomized males of the same strain to induce pregnancy or PSP respectively. The morning of finding a vaginal plug was designated day 1 of pregnancy. Implantation sites (IS) on days 5, 6, or 7 were visualized by i.v. injection of 1% Chicago Blue dye solution in saline (Paria et al. 1993). Mice were housed in the semi-barrier animal care facility according to NIH and institutional guidelines for laboratory animals.

Blastocyst transfer to pseudopregnant mice

Day 4 blastocysts were transferred to the uteri of recipients in the morning (1000 h) of various days of PSP. Recipient mice were killed at 0900 h on designated days of PSP. P₄ (Sigma) was supplemented to several groups of days 6 and 7 pseudopregnant mice by daily injection from day 5 to the day when the mice were killed. Time of injection is indicated in Table 1. The number of IS was recorded by i.v. injection (0.1 ml/mouse) of Chicago Blue dye solution (1% in saline) 48 h after embryo transfer. Mice were killed 5 min later and IS were demarcated as discrete blue bands along the uteri.

Table 1

<table>
<thead>
<tr>
<th>Days of transfer</th>
<th>No. of recipients</th>
<th>No. of embryos transferred</th>
<th>No. of recipients with IS (%)</th>
<th>No. of IS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 4</td>
<td>5</td>
<td>60</td>
<td>5 (100)</td>
<td>31 (52)</td>
</tr>
<tr>
<td>Day 5</td>
<td>7</td>
<td>92</td>
<td>6 (86)</td>
<td>44 (48)</td>
</tr>
<tr>
<td>Day 6</td>
<td>8</td>
<td>94</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>(I) Day 6 (P₄; 0900 h)</td>
<td>15</td>
<td>221</td>
<td>9 (60)</td>
<td>50 (23)</td>
</tr>
<tr>
<td>(II) Day 6 (P₄; 1400 h)</td>
<td>6</td>
<td>69</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>(III) Day 7 (P₄; 0900 h)</td>
<td>7</td>
<td>90</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>(IV) Day 7 (P₄+F₂; 0900 h)</td>
<td>7</td>
<td>98</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

Day 4 blastocysts were transferred into uteri of recipients on various days of pseudopregnancy. P₄ supplemented recipients received an injection of P₄ (2 mg/mouse) on day 5 morning (0900 h): I, III, IV) or afternoon (1400 h): II) and continuous daily P₄ on the morning from day 6 until killed to examine IS. IV recipients were injected with F₂ (25 ng/mouse) along with P₄ on day 7 (0900 h) before embryo transfer. All recipients were killed 48 h after embryo transfer to examine IS by the blue dye method. Data for embryo transfer performed with day 4 and day 5 pseudopregnant recipients, used as control for other embryo transfers in this table, were previously published (Song et al. 2002).

Uterine cell type-specific proliferation in pseudopregnant mice

To examine whether uterine cell type-specific proliferation is associated with the uterine receptivity, the mice on days 4–6 of PSP received an injection (i.p.) of [methyl-³H] thymidine (25 μCi/0.1 ml; PerkinElmer, Boston, MA, USA) in the morning (0800 h) and were killed 2 h later. Nuclear uptake of [³H]thymidine was detected in uterine sections by autoradiography (Lim et al. 1997).

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In situ hybridization

In situ hybridization was performed as previously described (Das et al. 1994, Lim et al. 1997, Song et al. 2002). Small pieces of tissues were flash-frozen in liquid Histo-Freeze (Fisher Scientific, St Louis, MO, USA). Frozen sections (12 μm) were mounted onto poly-l-lysine-coated slides, fixed in cold 4% paraformaldehyde solution in PBS, acetylated, and hybridized at 45 °C for 4 h in hybridization buffer containing the 35S-labeled antisense cRNA probes. After hybridization, the sections were incubated with RNase A (RNase A, 20 μg/ml) at 37 °C for 20 min. RNase A-resistant hybrids were detected by autoradiography using Kodak NTB-2 liquid emulsion (Eastman Kodak, Rochester, NY, USA). Sections hybridized with sense probes served as negative controls. Sense and antisense 35S-labeled RNA probes were generated using the appropriate polymerases.

Results

Blastocysts can initiate attachment reaction in the non-receptive uterus beyond normal ‘window’ of uterine receptivity

Uterine environment at day 5 of PSP was considered non-receptive (Paria et al. 1993). When blastocysts are transferred to these uteri, IS are generally not visible if examined by 24 h. Recently, we have shown that blastocyst can still implant in the non-receptive uterus on day 5 of pregnancy and PSP beyond normal ‘window’ of uterine receptivity in mice, but they require longer time to initiate the attachment reaction (Song et al. 2002). This led us to hypothesize that blastocyst may initiate the implantation on extended days of PSP in conventionally non-receptive uterus. To test this hypothesis, we performed embryo transfer experiments to recipients on various days of PSP and examined IS 48 h later rather than 24 h by blue dye injection. As previously shown (Song et al. 2002), 48% of blastocysts implanted in the day 5 pseudopregnant uteri of recipients by 48 h after transfer. This was comparable to implantation rate of embryo transfers performed on day 4 of PSP (52%; Table 1). These clearly demonstrated that blastocysts can initiate the implantation process on day 5 of PSP in non-receptive uterus in mice. However, whether blastocyst can implant on later days of PSP in conventional non-receptive uterus still remain unanswered. To examine this, we performed embryo transfers to recipients on days 6 and 7 of PSP. In contrast, to comparable implantation rate of day 5 embryo transfer, blastocysts transferred to recipients on days 6 and 7 of PSP completely failed to implant even 48 h after embryo transfer (Table 1). These results indicate that day 5 pseudopregnant uterus is able to support attachment reaction but requires longer time (48 vs 24 h) to manifest the first sign of attachment reaction, the increased vascular permeability. However, this ‘window’ to initiate attachment reaction is shut off after day 5.

Progesterone supplementation retains uterine receptivity for blastocyst implantation on day 6 of PSP

The observation from embryo transfer experiments suggested that the uterine environment with respect to uterine receptivity for blastocyst implantation significantly changes between days 5 and 6 of PSP. Since it is well established that optimal levels of ovarian steroids are key regulators of uterine receptivity, we hypothesized that levels of progesterone could be a key factor to maintain uterine receptivity for blastocyst implantation. In fact, it was reported that P4 levels are maintained during days 3–5 of PSP and the levels significantly decrease by day 6 (Wakuda et al. 1999). Thus, we investigated whether exogenous ovarian steroids could further extend the receptive state for blastocyst implantation. We injected P4 (2 mg/mouse) daily (0900 h) from day 5 of PSP to the day when the recipients were killed and performed embryo transfers on day 6. Recipients were killed at 48 h after embryo transfer. Interestingly, 9 of 15 day 6 pseudopregnant recipients (60%) with daily P4 supplementation showed IS when examined at 48 h after embryo transfer (Table 1, I). This suggests that decreased level of P4 is a key factor for the uterus to become non-receptive (day 6). The number (23%) of IS visualized by the blue dye method in recipients on day 6 of PSP is lower than those of days 4 and 5 of PSP (52 and 48%) respectively, suggesting that P4 supplementation is not able to fully restore uterine receptivity on day 6. To examine if timing of P4 availability is important, we supplemented P4 in the afternoon (1400 h) rather than in the morning (0900 h) on day 5 to the recipient. Surprisingly, all the blastocysts transferred to those recipients failed to initiate the attachment reaction (Table 1, II). This result suggests that timely P4 supplementation is critical to maintain uterine environment for providing a more accessible condition for blastocyst implantation. Hormonal supplementation on day 7 of PSP did not help to improve implantation rate in day 7 PSP recipients (Table 1, III–IV). Collectively, the results suggest that critical changes in uterine physiology occur in the uterus between days 5 and 6 of PSP.

Uterus responds to decidualization stimuli beyond normal ‘window’ of uterine receptivity

Above results show that blastocysts are capable of initiating attachment reaction beyond normal ‘window’ of receptivity under appropriate P4 level as judged by increased vascular permeability at the site of implantation. The attachment reaction is immediately followed by decidual response by stromal cells underlying the luminal epithelial cells contacting the blastocyst. As decidual response is a critical component of successful implantation, we tested whether uteri of pseudopregnant recipients on different days respond to an artificial stimulus to induce decidualization beyond the normal
‘window’ of uterine receptivity. We gave an intraluminal oil infusion to recipients on days 4, 5, or 6 of PSP and examined the extent of decidual response 4 days later. Artifically induced decidualization occurred in most of the uteri of days 4 and 5 of PSP (5/6 and 6/8), but not in the uteri of day 6 of PSP (0/7; Fig. 1). To investigate whether P_4 supplementation sustain the uterine responsiveness to a deciduogenic stimulus on day 6 as in the case of the attachment reaction, we gave P_4 (2 mg/mouse) injections on days 5 and 6 of PSP (0900 h) in this experimental model. As shown in Fig. 1, P_4 injection improved decidual responses in day 6 pseudopregnant mice (5/17) although fold increases in uterine weight (7.4 ± 0.9) and percentage of mice with decidualization responses (29%) were lower than those of days 4 and 5 of PSP (12.1 ± 2.0 and 12.8 ± 1.2 fold increases in uterine weight, and 83 and 75% of mice respectively). These results collectively show that initial attachment reaction and subsequent decidual response to the extent comparable to day 4 pseudopregnant uterus can occur on day 5 of PSP, but not thereafter. In addition, P_4 supplementation partially improves the uterine condition on day 6 of PSP to support attachment reaction and decidualization.

**Cell proliferation profile is altered in the uterus in non-receptive phase**

In mice, the establishment of the receptive uterus for supporting implantation is regulated by coordinated effects of P_4 and E_2 on differential cell proliferation and gene expression (Huet et al. 1989). We suspected that failure of implantation and decidualization on day 6 of PSP is due to uterine delinquency arising from abnormal cell proliferation and/or differentiation. Thus, we compared uterine cell proliferation profiles between days 4 and 6 of PSP by [^3H]thymidine incorporation (Fig. 2). As previously observed (Huet et al. 1989), proliferation was restricted to stromal cells. However, no difference in proliferation pattern was noted between days 4 and 5 of PSP. However, [^3H]thymidine incorporation was aberrantly noted in luminal epithelial cells with very low to undetectable levels in the stroma (Fig. 2) in day 6 pseudopregnant mice. In addition, the number of proliferating cells on day 6 of PSP was quite lower than those on days 4 and 5 of PSP. Exogenous supplement of P_4 (2 mg/mouse) on day 5 of PSP (0900 h) maintained normal uterine cell proliferation profiles in some uteri of day 6 pseudopregnant mice.

**Figure 1** Experimentally induced decidualization in mice on days 4–6 of pseudopregnancy (PSP). Female mice received intraluminal oil infusion on days 4–6 of PSP. A group of day 6 pseudopregnant mice (day 6 (P_4)) was given with P_4 (2 mg/mouse) by daily injection from day 5 (0900 h) to the day when killed. Mice were killed 4 days after oil infusion and uterine weights were recorded. Fold increases denote comparison of weights between infused and non-infused uterine horns. Results of days 4 and 5 of PSP, used as control for decidualization with day 6 of PSP in this experiment, were previously published (Song et al. 2002). The numbers above bars indicate the numbers of responding mice/total mice. Results are mean ± S.E.M.

**Figure 2** Nuclear incorporation of [^3H]thymidine in proliferating uterine cells on days 4–6 of pseudopregnancy (PSP). Mice on days 4–6 of PSP received an injection (i.p.) of [^3H]thymidine in the morning (0800 h) and were killed 2 h later. A group of day 6 pseudopregnant mice (day 6 (P_4)) was given with a single injection of P_4 (2 mg/mouse) on day 5 (0900 h). Note nuclear [^3H]thymidine uptake in epithelial cells on day 6 of PSP, but in stromal cells of uteri of day 6 pseudopregnant mice injected with P_4 on day 5. Patterns of [^3H]thymidine incorporation in various days of PSP were shown under darkfield at 40X (left panel) and 200X (right panel) respectively. These experiments were repeated thrice with similar results.
The result that uteri on day 6 PSP no longer maintain cell proliferation profile of typical P₄ dominance suggests that the uterus on this day possibly undergoes critical change in hormonal milieu leading to uterine refractoriness to implantation.

**Differential expression of implantation-related genes during changing uterine receptivity**

Plasma levels of P₄ during pregnancy or PSP is one principal factor to provide the receptive environment by regulating certain local mediators. Thus, we examined expression of several implantation-related genes, such as COX-1 (Ptgs1), Amphiregulin (Areg), Hoxa10 (Hoxa10), Flk-1(Kdr), and LIF (Lif) using *in situ* hybridization on days 4–6 of PSP to investigate whether change in hormonal milieu on day 6 of PSP is accompanied by aberrant expression patterns of these genes (Figs 3 and 4). All of these genes are expressed in a cell type-specific manner during implantation (Chakraborty et al. 1995, Das et al. 1995a, Benson et al. 1996, Song et al. 2000). Ptgs1, as reported previously, was expressed mainly in luminal epithelium with modest expression in glandular epithelium on day 4. Interestingly, the accumulation of Ptgs1 mRNA in the luminal epithelium gradually decreased on day 5 and was no longer detected on day 6, while its expression in the glandular epithelium was intensified on day 6. Areg was expressed in the entire luminal epithelium on day 4, but gradually decreased and became almost undetectable on day 6. However, Hoxa10 and Kdr maintained similar expression patterns in the stroma throughout this period. Since Hoxa10 and Areg are both P₄-regulated genes, it is interesting to note that only the epithelial expression of Areg, but not the stromal expression of Hoxa10, decreases to undetectable levels on day 6 when blood levels of P₄ sharply decrease (Wakuda et al. 1999). Surprisingly, while exogenous P₄ supplementation partly extends the uterine receptivity for the attachment reaction and deciduization, the expression patterns of Ptgs1 and Areg on day 6 were not influenced by this treatment.

In contrast to implantation-related genes examined above, P₄ supplementation had an effect on the expression of Lif (Fig. 4). Lif, expressed in uterine glands prior to implantation on day 4 of pregnancy (Bhatt et al. 1991, Song et al. 2000), maintained expression in glands on days 4 and 5 of PSP. However, the expression rapidly decreased and became undetectable on day 6 of PSP (Fig. 4). Although it was previously shown that Lif expression is mainly regulated by estrogen (Bhatt et al. 1991, Shen & Leder 1992), P₄ supplementation in some day 6 pseudopregnant mice maintained its expression in uterine glands (arrows in the right panel of bottom). Collectively, these results suggest that uterine environment on day 6 of PSP undergoes certain molecular changes that reduce the efficiency of implantation and that P₄ is a key factor, even if not a sole one, to retain uterine environment for blastocyst implantation.

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**Figure 3** Expression of implantation-related genes in uteri of days 4–6 of pseudopregnant mice. *In situ* hybridization of Areg, Ptgs1, Hoxa10, Kdr mRNAs in uterine sections on days 4–6 of PSP are shown under darkfield at 40×. A group of day 6 pseudopregnant mice (day 6 (P₄)) was given with a single injection of P₄ (2 mg/mouse) on day 5 (0900 h). le, Luminal epithelium; ge, glandular epithelium; s, stroma; myo, myometrium. These experiments were repeated twice with similar results.
among implantation-specific genes, LIF is considered critical for implantation since LIF\(^{-/-}\) mice show implantation and decidualization failures (Stewart et al. 1992, Song et al. 2000). Thus, it is interesting to see that LIF is expressed in uterine glands as long as uterus is receptive for blastocyst implantation (days 4 and 5; Fig. 4). LIF expression is very low to undetectable on day 6 of PSP when blastocyst fails to initiate implantation. These results suggest that LIF is a critical factor contributing to the receptive state of uterus for blastocyst implantation. One explanation of partial rescue by P4 is that other negative factors for receptivity increase in the uterus as time passes. One example is the endocannabinoid signaling, which was previously identified as an important regulator of uterine receptivity for implantation (Das et al. 1995b, Paria et al. 1996, Schmid et al. 1997). The level of anandamide, an endogenous cannabinoid, gradually increases with changing uterine sensitivity from receptive (on day 4) to non-receptive phase (on day 6; Paria et al. 2001). In addition, its level in LIF\(^{-/-}\) mice was higher than that of wild-type mice on day 4 of pregnancy (Paria et al. 2001). It will be interesting to investigate whether P4 supplementation to non-receptive uterus affects levels of anandamide or not.

Our present study shows that blastocysts can initiate implantation beyond the normal ‘window’ of uterine receptivity when P4 level is appropriate. However, there is evidence that temporally deferred implantation beyond normal ‘window’ of uterine receptivity in wild-type mice may accompany various defects in embryo developments leading to embryonic demise before birth (Song et al. 2002, Wang & Dey 2006). One-day delay of implantation process in cPLA2\(^{-/-}\) mice indeed results in defective postimplantation developments (Song et al. 2002). These results are consistent with increased risk of early pregnancy loss in embryo implantation with sub-optimal uterine receptivity in humans (Wilcox et al. 1999). While our work provides solid evidence that P4 is one crucial factor regulating uterine receptivity, other factors involved in optimizing uterine environment for implantation needs further identification.

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