Effects of Maternal Caffeine Consumption on Ovarian Follicle Development in Wistar Rats Offspring

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Abstract

Background: In recent years concerns have been raised about human reproductive disorders, specially the effects of environmental factors on human fertility and pregnancy outcome. Therefore, the present study was designed to assess the effects of maternal caffeine consumption on ovarian follicles development in rat offspring.

Methods: 60 pregnant female rats were randomly divided into a control and two experimental groups. The rats in the two experimental groups received caffeine via drinking water during gestation (26 and 45 mg/kg) and lactation (25 and 35 mg/kg). The ovaries of the offspring were removed at 7, 14, 28, 60, 90 and 120 days after birth, and fixed in Bouin’s solution. By preparing serial tissue sections, structural changes in ovarian follicles and corpora lutea were studied during postnatal development.

Results: The weight of ovaries decreased significantly (p<0.05) in the high dose caffeine-treated group at all stages of postnatal development. Significant (p<0.05) decreases were seen in the number of primordial follicles from day 7 to 120 after birth in the high dose caffeine-treated group. Moreover, the number of primary and secondary follicles decreased significantly on days 7, 14 and 28 as did the number of antral follicles on days 14 and 28 after birth (p<0.05) in the high dose caffeine-treated group. The diameter of secondary and antral follicles decreased significantly (p<0.05) in high dose caffeine-treated group on the early days of postnatal development. No statistically significant differences were seen in the number of corpora lutea between the groups.

Conclusion: The present study shows that caffeine consumption during gestation and lactation affects the early stages of ovarian follicle development and reduces reproductive efficiency in the offspring of Wistar rats.

Keywords: Caffeine, Fertility, Ovarian follicles, Postnatal development.


Background

In recent years, concerns have been raised regarding the increases in human reproductive disorders. Exposure to environmental and occupational toxicants and progressive changes in many aspects of lifestyle, including dietary habits, has been shown to deteriorate reproductive health, thus, affecting the ability of couples to conceive and maintain a healthy pregnancy (1).

Among dietary factors, caffeine consumption has been found to adversely affect reproduction (2). Caffeine is a naturally occurring alkaloid found in the seeds, leaves and fruits of more than 60 plants such as in coffee and cocoa beans, kola nuts, and tea leaves. Caffeine is present in a wide variety of foods and beverages including coffee, tea, cocoa, chocolate, colas and energy drinks, and also in a number of prescription drugs including cold and flu remedies, headache treatments, diet pills, diuretics and stimulants (3). The amount of caffeine in foods and beverages varies widely depending on
the type of product and the preparation methods. In general, brewed coffee contains the highest amount of caffeine, with an average of 137 mg per an-8-ounce cup and chocolate contains the lowest amount of caffeine (4). The total daily intake of caffeine from all sources is estimated to be about 3-7 mg/kg per day or 200 mg/day (5). Moreover, it has been shown that caffeine in shampoos is absorbed through the skin, mostly through hair follicles, and reaches the blood stream (6).

Peak plasma caffeine concentration is reached between 15-120 min after oral ingestion in humans. Caffeine half-life is about three hours but it increases to 5.6 hours in the first trimester and to 18 hours in the 35th week of pregnancy (7). Caffeine crosses the placenta easily and is found in both the fetus and in newborn infants (9).

Caffeine consumption has been found to be associated with low birth weight, small head, cleft palate, retardation, miscarriage or spontaneous abortion, increased incidences of digital defects and delayed ossification (9, 10). Wilcox et al. found a 50% reduction in the probability of conception per cycle with intake of one cup of coffee per day (11). Jagilo et al. reported that subcutaneous administration of 25 mg/kg per day of caffeine prevented hormonally induced superovulation in adult mice (12). Similarly, it was found that oral gavage of 136 mg/kg per day of caffeine, 5 days per week for a total of 100 days, blocks normal oogenesis in adult rats (13). Furthermore, it has been shown that caffeine prolongs the meiotic arrest of porcine oocytes at the germinal vesicle stage (14). However, epidemiological studies in Danish women showed no association between delayed conception and consumption of caffeinated beverages (15, 16). Likewise, Caan et al. found that women who drank more than half a cup of tea per day had a significant increase in fertility (17). Furthermore, caffeine administration during pregnancy did not affect the rate of early mitotic proliferation of germ cells at day 20 of pregnancy in rats, nor did it prevent their development or decrease their meiosis (18). Caffeine treatment can prevent the decline in the developmental potential of ovine oocytes matured and aged in vitro (19).

Regarding the conflicting results of epidemiological studies on caffeine and its effects on reproductive outcomes (20) and caffeine-containing foods and beverages are so widely consumed by most human populations of the world, its health effects have been and are still being studied extensively. The present study was designed to investigate the effects of maternal caffeine consumption during gestation and lactation on postnatal development of ovaries in the offspring of Wistar rats.

**Methods**

*Animals:* Wistar rats were obtained from animal house of Jondishapour Medical Sciences University of Ahwaz and kept under specific conditions on a constant 12-hour light/dark cycle and at a controlled temperature of 22 ± 2°C. Standard pellet food and distilled water were available ad libitum. Female Wistar rats (100 ± 10 days old) were mated overnight at a 3:1 females:male ratio. Vaginal smears were daily prepared and examined for the presence of sperm. The day of sperm detection in vaginal smears was considered day 0 of pregnancy. 60 Pregnant female Wistar rats were randomly divided into three equal groups; a control group and two treatment groups. The two treatment groups, respectively received caffeine via drinking water during gestation (26 and 45 mg/kg) and lactation (25 and 35 mg/kg) (23, 24) i.e. until day 21 after birth. The doses were established from related reproductive and developmental studies. On days 7, 14, 28, 60, 90 and 120 five pups were randomly selected, weighed and their ovaries were removed under chloroform inhalation anesthesia. The ovaries were trimmed of fat and extraneous tissue, weighed and fixed by immersion in Bouin’s solution for 24 hours.

*Microscopic Study:* Following tissue processing, 5 µm serial paraffin sections were prepared and stained by haematoxylin-eosin. For microscopic examination, sections were selected using a non-random 10% sampling method and ovarian follicles and corpora lutea were counted in every 10th section of the ovary (25), in a fashion that each counted section was separated by a distance of approximately 50-60 µm from the next 10th section.

Later, the mean number of ovarian follicles and corpora lutea of each ovary were calculated in the
selected sections. Differential follicle counting and categorizing were performed blindly. Ovarian follicles were classified on the basis of ovarian follicle morphology. Follicles containing a single layer of squamous follicular cells were considered as primordial. A primary follicle contains an oocyte surrounded by a single layer of cuboidal follicular cells; the secondary follicle contains more than one layer of follicular cells around the oocyte. Follicles containing scattered spaces or a distinct antrum were considered as antral (26). All the follicles were classified as either healthy or atretic, respectively, according to the absence or presence of signs of oocyte and/or granular degeneration such as pyknosis of the nucleus, infolding of the cell wall in oocyte, ingestion of granulosa cells within the antral cavity, pulling away of granulosa cells from the basement membrane, infolding or thickening of base membrane and uneven layers of granulosa cells (27).

For measuring the diameter of ovarian follicle in each developmental stage, 45 microscopic fields were randomly chosen in each rat. Then, using the ocular micrometer of a light microscope (Olympus EH, America Inc.), at a magnification of 10×, the diameter of each ovarian follicle were measured. To avoid recounting the same follicle, only individual follicles, containing an oocyte with a nucleus, were evaluated.

**Statistical Analysis:** The data were analyzed using SPSS, version 10.0 for Windows. Body and ovarian weights, the number and diameter of follicles and corpora lutea in the control and caffeine-treated groups were compared by one-way analysis of variance (ANOVA) and Tukey’s post hoc test. Comparisons between different groups were made in each developmental stage, independent from other days of postnatal development. The differences were considered to be significant when \( p<0.05 \).

**Results**

Mean body weight showed significant (\( p<0.05 \)) decreases in high dose caffeine-treated group in all stages of postnatal development in comparison with the control group. There were significant (\( p<0.05 \)) differences between the mean ovary weight in high dose caffeine-treated and control groups in all stages of postnatal development. No significant differences were seen between the mean body and ovary weight in low dose caffeine-treated and the control groups in all stages of postnatal development (Table 1).

The mean number of primordial follicles decreased significantly (\( p<0.05 \)) in high dose caffeine-treated group from the 7th to 120th day in comparison with the control group (Table 2).

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**Table 1.** Distribution of body weight (gr) and ovary weight (mg) in the controls and caffeine-treated offspring of Wistar rats during different stages of postnatal development (Mean±SEM)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Age of Pups (day)</th>
<th>Control</th>
<th>Caffeine-treated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Body weight (gr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>8.91±0.17(^a)</td>
<td>7.84±0.41(^b)</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>12.14±0.76(^a)</td>
<td>11.35±0.28(^b)</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>25.00±1.18(^a)</td>
<td>22.75±1.21(^b)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>58.17±3.62(^a)</td>
<td>52.96±2.89(^b)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>82.61±4.18(^a)</td>
<td>77.14±3.62(^b)</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>95.12±4.26(^a)</td>
<td>91.65±4.01(^b)</td>
</tr>
<tr>
<td></td>
<td>Ovary weight (mg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.20±0.15(^a)</td>
<td>1.80±0.18(^b)</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>6.30±0.20(^a)</td>
<td>5.80±0.31(^b)</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>18.40±1.33(^a)</td>
<td>17.50±1.24(^b)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>35.00±2.32(^a)</td>
<td>32.70±2.22(^b)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>45.61±3.54(^a)</td>
<td>40.90±3.44(^b)</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>48.33±5.01(^a)</td>
<td>46.60±4.41(^b)</td>
</tr>
</tbody>
</table>

\( a,b \) Different superscripts in the same row indicate significant difference between groups (\( P<0.05 \))
Maternal caffeine consumption affects

Significant ($p<0.05$) decreases were observed in the mean number of primary and secondary follicles on days 7, 14 and 28 in both treatment groups in comparison with the controls. There were no significant differences between the mean number of primary and secondary follicles in the controls and both treatment groups on days 60, 90 and 120 (Table 2).

Antral follicles were not seen on day 7 in any of the experiment groups. The mean number of antral follicles decreased significantly ($p<0.05$) in both treatment groups on days 14 and 28 in comparison with the control group (Table 2). No significant differences were seen between the mean number of antral follicles in the control and both treatment groups on days 60, 90 and 120 (Table 2).

There were no significant differences between the means of primordial and primary follicles in diameter in the control and treatment groups in all stages of postnatal development. The mean for secondary follicles diameter decreased significantly ($p<0.05$) in high dose caffeine-treated group on days 7, 14, 28 and 60 in comparison

### Table 2. The number of ovarian follicles in the control and caffeine-treated offspring of Wistar rats during different stages of postnatal development (Mean±SEM)

<table>
<thead>
<tr>
<th>Follicular stage</th>
<th>Age of pups (days)</th>
<th>Groups</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>Caffeine-treated</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low dose</td>
<td>High dose</td>
<td></td>
</tr>
<tr>
<td>Primordial F.</td>
<td>7</td>
<td>48.57±5.20a</td>
<td>44.57±4.27ab</td>
<td>39.57±5.27b</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>38.70±4.72a</td>
<td>36.40±4.27ab</td>
<td>32.10±3.27b</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>25.50±3.14a</td>
<td>21.20±2.25ab</td>
<td>17.10±1.36b</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>19.00±1.67a</td>
<td>16.33±1.21ab</td>
<td>11.41±1.28b</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>17.66±1.46a</td>
<td>12.73±1.18ab</td>
<td>10.33±1.16b</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>15.32±1.25a</td>
<td>13.87±1.20ab</td>
<td>10.65±1.04b</td>
</tr>
<tr>
<td>Primary F.</td>
<td>7</td>
<td>35.90±4.97a</td>
<td>28.10±3.21b*</td>
<td>25.90±2.39**</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>30.40±3.27a</td>
<td>22.90±2.27b*</td>
<td>20.40±2.13**</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>18.08±2.25a</td>
<td>9.16±1.18b*</td>
<td>8.75±1.11b**</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>8.26±1.21</td>
<td>6.20±0.27</td>
<td>5.80±0.22</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>8.40±1.38</td>
<td>5.13±0.24</td>
<td>6.53±0.62</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>6.43±0.03</td>
<td>6.30±0.25</td>
<td>5.05±0.23</td>
</tr>
<tr>
<td>Secondary F.</td>
<td>7</td>
<td>3.00±0.15a</td>
<td>1.90±0.11b*</td>
<td>1.50±0.11b**</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>16.80±1.45a</td>
<td>10.70±1.28b*</td>
<td>9.00±1.15b**</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>11.75±1.41a</td>
<td>5.75±0.22b*</td>
<td>4.00±0.22b**</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>8.10±1.20</td>
<td>6.30±0.28</td>
<td>5.90±0.19</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>3.93±0.15</td>
<td>3.50±0.14</td>
<td>3.44±0.14</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>4.64±0.17</td>
<td>3.55±0.18</td>
<td>3.84±0.16</td>
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<tr>
<td>Antral F.</td>
<td>7</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>3.62±0.15a</td>
<td>1.25±0.10b*</td>
<td>1.04±0.10b**</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>4.83±0.18a</td>
<td>2.04±0.12b*</td>
<td>2.00±0.12b**</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>4.80±0.17</td>
<td>3.30±0.15</td>
<td>3.20±0.16</td>
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<tr>
<td></td>
<td>90</td>
<td>5.07±0.28</td>
<td>4.41±0.21</td>
<td>4.23±0.18</td>
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<tr>
<td></td>
<td>120</td>
<td>7.65±0.41</td>
<td>6.71±0.30</td>
<td>6.46±0.28</td>
</tr>
</tbody>
</table>

a,b Different superscripts in the same row indicate significant difference between groups ($P<0.05$)
* $p<0.01$, ** $p<0.001$
F: Follicle, N: Not seen

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with the controls. Moreover, significant \( (p<0.05) \) decreases were seen between the mean of antral follicle diameter in the control and high dose caffeine-treated group on the 14\textsuperscript{th}, 28\textsuperscript{th} and 60\textsuperscript{th} days (Table 3).

There were significant \( (p<0.05) \) increases in the mean number of atretic follicles on days 7, 14 and 28 in both treatment groups in comparison with the controls. No statistically significant differences were seen between the mean number of corpora lutea in the controls and both treatment groups on the 60\textsuperscript{th}, 90\textsuperscript{th} and 120\textsuperscript{th} days.

### Discussion

The aim of present study was to establish whether in utero and lactational exposure of Wistar rats to caffeine affects ovarian development in their offspring during pre- and post puberty development. The results clearly showed that high dose maternal caffeine consumption during gestation and lactation significantly reduced ovarian weight and primordial follicle population and diminished fertility and reproductive efficiency in the offspring of Wistar rats. These alterations in the ovary were associated with a significant growth retardation of the female off-

### Table 3. The diameter of ovarian follicles (µm) in control and caffeine-treated offspring of Wistar rats during different stages of postnatal development (Mean±SEM)

<table>
<thead>
<tr>
<th>Follicular stage</th>
<th>Age of Pups (day)</th>
<th>Control</th>
<th>Caffeine-treated</th>
<th>Caffeine-treated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td>Low dose</td>
<td>High dose</td>
</tr>
<tr>
<td>Primordial F.</td>
<td>7</td>
<td>19.50±1.80</td>
<td>19.30±2.41</td>
<td>18.90±1.08</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>20.25±2.85</td>
<td>19.59±1.82</td>
<td>19.30±1.32</td>
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<tr>
<td></td>
<td>28</td>
<td>21.60±3.10</td>
<td>20.92±2.73</td>
<td>20.25±2.36</td>
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<td></td>
<td>60</td>
<td>21.35±3.83</td>
<td>20.74±2.55</td>
<td>20.79±1.47</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>20.90±2.90</td>
<td>20.25±1.18</td>
<td>20.43±2.16</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>20.74±2.45</td>
<td>20.32±2.20</td>
<td>20.45±2.24</td>
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<tr>
<td>Primary F.</td>
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<td>45.29±2.28</td>
<td>44.74±2.20</td>
<td>44.30±2.10</td>
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<tr>
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<td>14</td>
<td>50.24±4.26</td>
<td>49.73±2.67</td>
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<td>50.23±3.28</td>
<td>49.58±2.03</td>
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<td></td>
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<td>51.55±2.01</td>
<td>50.67±3.39</td>
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<tr>
<td></td>
<td>90</td>
<td>51.80±3.84</td>
<td>51.35±2.53</td>
<td>50.61±3.36</td>
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<tr>
<td></td>
<td>120</td>
<td>51.84±2.86</td>
<td>51.40±2.57</td>
<td>50.80±3.41</td>
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<td>Secondary F.</td>
<td>7</td>
<td>70.10±3.27(a)</td>
<td>68.20±4.10(ab)</td>
<td>61.30±3.87(b)</td>
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<tr>
<td></td>
<td>14</td>
<td>88.72±4.70(a)</td>
<td>83.59±3.47(ab)</td>
<td>78.55±4.31(b)</td>
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<tr>
<td></td>
<td>28</td>
<td>109.89±4.41(a)</td>
<td>100.81±4.05(ab)</td>
<td>94.65±3.34(b)</td>
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<tr>
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<td>60</td>
<td>112.93±5.47(a)</td>
<td>106.88±5.49(ab)</td>
<td>99.37±4.83(b)</td>
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<tr>
<td></td>
<td>90</td>
<td>116.39±5.56</td>
<td>112.32±4.61</td>
<td>110.33±3.26</td>
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<tr>
<td></td>
<td>120</td>
<td>117.65±4.60</td>
<td>114.71±5.10</td>
<td>111.46±5.39</td>
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<td>Antral F.</td>
<td>7</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
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<td>200.00±6.12(a)</td>
<td>196.62±4.47(ab)</td>
<td>190.15±4.67(b)</td>
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<td>222.65±5.80</td>
<td>220.71±6.16</td>
<td>217.42±5.33</td>
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\(a,b\) Different superscripts in the same row indicate significant difference between groups \( (P<0.05) \)

F: Follicle, N: Not seen
Maternal caffeine consumption affects
spring. It seems that reductions in the number of
primordial follicles, the number and diameter of
secondary and antral follicles and the increase in
the number of atretic follicles caused a significant
decrease in ovarian weight in different stages of
postnatal development.

In this study, reduction in number of primordial,
primary and secondary follicles increased from
birth to 28 days onwards but decreased then after,
up to the end of the study (120th day) in both treat-
ment groups. However, the highest ovarian weight
decline was seen on day 7 after birth which
continued until the 120th day in both treatment
groups.

Female fertility depends on the supply and mat-
uration of the ovarian germ cells, i.e., the oocytes
and the differentiation and proliferation of ovarian
somatic cells, or granulosa and thecal cells (28).
During folliculogenesis, oocytes grow and they
are surrounded by an increasing number of
granulosa cell layers. From the preantral stage
onward, theca cells differentiate outside the
follicles (29). Improper ovarian differentiation or
folliculogenesis, due to intra- or extra-ovarian
regulation defects, often results in premature
ovarian failure, leading to infertility (30). In rats,
the formation of primordial follicles is completed
by postnatal day three or four (31). Most primor-
dial follicles remain quiescent, but some grow and
undergo transition into the primary follicle stage.
High numbers of preantral and antral follicles
would be present from day 9 to 20 (32), and the
first estrus and ovulation will occur between days
35-42 after birth (33).

The present study showed that caffeine treatment
altered the number of primordial follicles in the
resting pool from day 7 until day 120 in the high
dose caffeine group.

For reproductive toxicants that cause direct dam-
age to ovarian follicles, the stage of development
at which follicles are destroyed determines the
impact that exposure to the chemical will have on
reproduction (34). Chemicals that extensively des-
troy primordial follicles cause permanent infertil-
ity and premature ovarian failure, since once a
primordial follicle is destroyed, it cannot be
replaced. Destruction of primordial follicles will
have an irreversible effect on reproduction until
such a time that recruitment for the number of
growing and antral follicles can no longer be
supported (35, 36). It seems that caffeine could
interfere with cell division resulting in decreased
number of cells and cell death. Axelrod and
Reichenthal described this hypothesis that caf-
feine acts by genetic damage to the cells replic-
ating DNA (37). Comet assay studies indicate
that caffeine-mediated increases in radiation risk
of embryos is due to the inhibition of DNA repair
(38). Furthermore, Jagiello et al. (1972) reported
meiosis suppression by caffeine in female mice
(9).

However, our findings indicated that unlike days
7, 14 and 28, there were no significant differences
in the number of growing follicles on days 60, 90
and 120 after birth in the treatment groups. More-
over, the diameter of secondary and antral fol-
lies and the number of corpora lutea in the treat-
ment groups did not differ with that of the control
group on days 60, 90 and 120 after birth. Thus, it
seems that caffeine exposure has transient effects
on follicular development and ovulation in the
offspring of Wistar rats during the postnatal
development. This could be due to the fact that
caffeine does not accumulate in the body over the
course of time and it is normally excreted within
several hours of consumption. Chemicals that
selectively damage large growing or antral fol-
lies only temporarily interrupt reproductive
function because these follicles can be replaced by
recruitment from the greater pool of primordial
follicles. Thus, these chemicals produce a readily
reversible form of infertility that is manifested
relatively soon after exposure period (35, 36).

Conclusion
The present study showed that maternal caffeine
consumption during gestation and lactation affects
the early stages of follicular development and
reduces reproductive efficiency in the offspring of
Wistar rats.

Acknowledgement
The authors wish to thank the vice-chancellor for
research of Shahid Chamran University of Ahwaz
providing for the research grant. No conflict of
interest existed.

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