Melatonin enhances leptin expression by rat adipocytes in the presence of insulin

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Melatonin is produced and secreted by the pineal gland, with a circadian rhythm characterized by low levels during the day and peak values at night (5, 36). It plays an important role as an interface among the cyclic environment, physiological rhythms, and neuroendocrine processes (22, 23). Even though melatonin has been shown to reduce body mass in diet-induced obesity and old rats (47, 63, 50), and previous studies have suggested a possible role for this hormone in maintaining optimal energy balance (9, 65), the relationship between melatonin and leptin remains to be fully clarified.

Therefore, to assess the involvement of melatonin on leptin expression, we specifically investigated its direct action on leptin release and gene expression in isolated rat adipocytes. Considering that melatonin acts directly on adipocytes through specific pertussis toxin-sensitive Gi protein-coupled receptors (GPCR) MT1 and MT2 (9, 65), we hypothesized that the activation of these receptors might exert a positive modulation on leptin production by lowering cAMP levels.

To confirm this hypothesis we evaluated 1) the ability of isolated adipocytes to synthesize and release leptin under melatonin treatment, 2) how they respond to insulin and/or dexamethasone in combination with melatonin, and 3) the mechanism underlying the action of melatonin over these parameters. Our results not only revealed a new mechanism for regulation of leptin expression by melatonin acting through MT1 receptors but also showed a potential cross talk between melatonin and insulin, where the insulin receptor and its convergent target Akt are coactivated by melatonin, a GPCR-binding hormone.

MATERIALS AND METHODS

Preparation of adipocytes. Male adult Wistar rats (8 wk old) were purchased from the Animal Resource of the Institute of Biomedical Sciences, University of São Paulo, São Paulo, Brazil, and were kept on a 12:12-h light-dark cycle (lights on at 0700) in a room with controlled temperature (23 ± 1°C). Animals were housed in groups of three to four in plastic cages with food (balanced chow pellet diet, Nuvilab CR1; Nuvital, Colombo, PR, Brazil) and water ad libitum. Rats were killed at 0800 by decapitation. The abdominal wall was opened, and the periepididymal fat pads were excised and processed.

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Dulbecco’s modified Eagle’s medium (DMEM; Invitrogen, Carlsbad, CA) containing 20 mM HEPES, 5 mM glucose, 1% BSA (fraction V; Sigma Chemical, St. Louis, MO), antibiotics (100 μg/ml penicillin and 100 μg/ml streptomycin, Invitrogen) and 1 mg/ml collagenase type II (Sigma), pH 7.4. The mixture was incubated in an orbital shaker (New Brunswick Scientific, Edison, NJ) at 150 rpm for 30 min at 37°C. The isolated adipocytes were filtered through a fine plastic mesh, transferred to a conical (50-ml) plastic tube, and washed three times in the same buffer without collagenase (25 ml/wash). After the final wash, cells were allowed to rest in the same buffer for 4 h at 37°C before being seeded as described below. According to our experience, this procedure completely abolishes any previous in vivo interference on cell metabolism and brings the cells to a similar metabolic state before the start of the following incubations. Adipocyte viability was tested with trypan blue, and the cell number was determined as previously described (21).

**Incubations of adipocytes.** Incubations were set up in six-well culture plates. Before the cells were incubated, the adipocytes were washed three times, and the medium was completely aspirated. From the resultant adipocyte pack, an aliquot of cells was added to wells containing 4 ml of incubation buffer (similar to the digestion buffer, except that collagenase type II was absent and 10% fetal bovine serum was added) to obtain a final cell concentration of 4 × 10⁶ cells/ml, followed by the addition, where indicated, of 1 nM melatonin, 5 nM insulin, 7 nM dexamethasone, 75 ng/ml pertussis toxin (PTX; Calbiochem-Novabiochem, La Jolla, CA), 25 μM forskolin (or varying concentrations), or melatonin receptor antagonists: 10 μM luzindole (2-benzyl-N-acetyltryptamine) or 10 μM 4P-DPT (4-phenyl-2-propionamidotetraline; Tocris Cookson, Ellisville, MO). All other drugs were purchased from Sigma. The incubation was carried out at 37°C in a 5% CO₂ atmosphere, usually for 6 h. At the end, aliquots of the medium were taken out and stored at −20°C for later determination of the leptin released, and the cells were collected for the analysis of leptin mRNA and the insulin intracellular signaling.

**RT-PCR assay for leptin gene expression.** All reagents were purchased from Invitrogen. Total RNA was extracted from isolated adipocytes by use of guanidine isothiocyanate-based TRIzol solution, according to the manufacturer’s specifications (17), and quantified spectrophotometrically at 260 nm with acceptable 260/280 ratios of 1.7 to 2.0. The RNA quality was also checked by 1% agarose gel electrophoresis, stained with ethidium bromide, and analyzed by scanning densitometry (Eagle Eye-Stratagene, model 401304, software Eagle Sight 3.2). Samples were normalized to the quantity of β-actin signal produced by RT-PCR and presented as arbitrary units of leptin mRNA relative to control. The DNA amplification product levels were carefully measured on the linear portion of the amplification curve.

**Leptin secretion.** Leptin levels were measured in the culture medium by radioimmunoassay (RIA) using a commercially available rat leptin kit (Linco Research, St. Charles, MO). The test sensitivity is 0.5 ng/ml leptin, and the intra-assay coefficient of variation was <5%. The secretion rate was expressed as nanograms of leptin released per 10⁶ cells per hour.

**Western blotting analysis.** After the incubations, adipocytes were washed three times in DMEM and homogenized in ice-cold buffer (100 mM Tris, pH 7.6, 1% Triton X-100, 0.1 mg/ml aprotinin, 2 mM PMSF, 10 mM NaVO₄, 10 mM NaF, 10 mM Na₃P₂O₇, and 10 mM EDTA) with a Polytron PT 2100 (Kinematica, Litt-Lucerna, Switzerland) set at maximum speed for 30 s. Insoluble material was removed by 20-min centrifugation at 12,000 × _g_ at 4°C. Protein concentration was measured by the Bradford method (Bio-Rad, Hercules, CA). Aliquots of the supernatant containing 3 mg of total protein were used for immunoprecipitation with anti-insulin receptor β-subunit antibody (α-IRβ) and protein A-Sepharose 6MB before sample treatment with Laemmli buffer and 6.5% SDS-PAGE, as described elsewhere (15). The nitrocellulose blots were incubated for 4 h at 22°C with α-IRβ or anti-phosphotyrosine antibody (α-pTyr) diluted in blocking buffer (3% nonfat dry milk). For Akt serine phosphorylation studies, equal amounts of protein (30 μg) were subjected to 8% SDS-PAGE and immunoblotted with anti-phospho(Ser⁴⁷³)-Akt antibody (α-pAkt). Electrophoretic proteins from the gel to nitrocellulose membrane was performed for 90 min at 120 V (constant). The filter was preincubated overnight at 4°C in blocking buffer (5% nonfat dry milk, 10 mM Tris, 150 mM NaCl, and 0.02% Tween 20) to reduce nonspecific protein binding to the nitrocellulose. To visualize the autoradiogram, we used the commercial enhanced chemiluminescence reagents (ECL, Amersham Biosciences, São Paulo, SP, Brazil) and protein A-Sepharose 6MB before sample treatment with Laemmli buffer and 6.5% SDS-PAGE, as described elsewhere (15). The nitrocellulose blots were incubated for 4 h at 22°C with α-IRβ or anti-phosphotyrosine antibody (α-pTyr) diluted in blocking buffer (3% nonfat dry milk). For Akt serine phosphorylation studies, equal amounts of protein (30 μg) were subjected to 8% SDS-PAGE and immunoblotted with anti-phospho(Ser⁴⁷³)-Akt antibody (α-pAkt). Electrophoretic proteins from the gel to nitrocellulose membrane was performed for 90 min at 120 V (constant). The filter was preincubated overnight at 4°C in blocking buffer (5% nonfat dry milk, 10 mM Tris, 150 mM NaCl, and 0.02% Tween 20) to reduce nonspecific protein binding to the nitrocellulose. To visualize the autoradiogram, we used the commercial enhanced chemiluminescence reagents (ECL, Amersham Biosciences, São Paulo, SP, Brazil) and protein A-Sepharose 6MB before sample treatment with Laemmli buffer and 6.5% SDS-PAGE, as described elsewhere (15).

**Statistical analysis.** IC₅₀ values were calculated from dose-response curves by nonlinear sigmoidal regression. Statistical analyses were performed by one-way or two-way ANOVA (for the time course studies) followed by Bonferroni post hoc tests, using GraphPad Prism, version 3.0, for Windows (GraphPad Software, San Diego, CA). The level of significance was set at _P_ = 0.05. Data were presented as means ± SE.

**RESULTS**

**Time course of leptin release in insulin- and/or dexamethasone-stimulated isolated adipocytes.** Figure 1 demonstrates the time course effects of insulin, dexamethasone, and the combination of the two hormones on the leptin release in isolated adipocytes. A significant increase was evident after 6 h of incubation with glucocorticoid alone or associated with insulin (2.5-fold the control value). Leptin alone did not stimulate the adipocytes or synergize the effect of dexamethasone. On the basis of these results, the 6-h incubation was chosen for the remaining assays.

**Effects of melatonin, insulin, and dexamethasone on leptin release and mRNA expression.** After 6 h of incubation, melatonin or insulin alone did not change the amount of leptin released by adipocytes compared with control cells (Fig. 2).
However, when adipocytes were incubated with insulin in the presence of melatonin, a significant increment on leptin release (120%; Fig. 2A) and mRNA content (50%; Fig. 2B) was observed. Dexamethasone alone increased leptin release (105%) and gene expression (50%). Simultaneous treatment with melatonin and dexamethasone did not result in any significant increment on leptin release and mRNA content compared with dexamethasone alone. Similarly, the addition of insulin did not result in any synergism with dexamethasone. However, when dexamethasone was associated with insulin and melatonin, a further increase in leptin release (250%) and in gene expression (100%) was obtained.

Melatonin prevented forskolin-induced inhibition of leptin release and gene expression. Considering that elevated cytoplasmatic cAMP levels inhibit leptin synthesis, forskolin, a potent stimulator of adenylyl cyclase and cAMP synthesis, was added to the incubations to further characterize whether the effects of melatonin on leptin expression is a cAMP-mediated event. A dose-response curve is depicted in Fig. 3, where a clear, sigmoid-shaped decay curve is seen in adipocytes treated with forskolin (IC50 = 6.1 ± 0.78 μM). In the same figure, the dashed curve shows the attenuating effect of melatonin. As noted, a rightward shift was observed in the forskolin decaying curve in the presence of melatonin (IC50 = 80.5 ± 2.6 μM). The next experiments (Fig. 4, A and B) were performed under a concentration of 25 μM forskolin, which was enough to elicit a nearly maximal inhibitory effect in non-melatonin-treated adipocytes and, on the other hand, was almost entirely suppressed in the presence of melatonin (1 nM).

In the absence of melatonin, forskolin treatment promoted an overall reduction (between 50 and 95%) in the leptin release. Melatonin addition completely antagonized this effect. Moreover, even in the presence of forskolin, melatonin was effective in its positive interaction with insulin alone (80%) or combined with dexamethasone (125%; Fig. 4A). The expression of leptin mRNA was also assessed in cells incubated with forskolin (Fig. 4B). These experiments revealed that forskolin was able to reduce basal (38%) as well as insulin/dexametha-

![Fig. 1. Time course of insulin (Ins) and/or dexamethasone (Dex) treatment on leptin release. Adipocytes from epididymal fat pads were isolated from male Wistar rats. Cells were incubated at 37°C for 6 h in the absence or presence of 5 nM insulin and/or 7 nM dexamethasone. Aliquots of the medium were collected at 0, 3, and 6 h for determination of leptin content by RIA. Data represent means ± SE of 4 independent experiments performed in duplicate. *P < 0.05 vs. control (–) after 6 h of incubation.](Image)

![Fig. 2. Effects of melatonin (Mel), insulin, and dexamethasone on leptin release (A) and gene expression (B). Isolated adipocytes were incubated at 37°C for 6 h in the absence or presence of 1 nM melatonin, associated or not with 5 nM insulin and/or 7 nM dexamethasone. A: aliquots of the medium were collected for determination of leptin content by RIA. Two sets of experiments are depicted in the graph. The 1st shows cell treatments without melatonin; the 2nd shows the same treatments in the presence of melatonin. Data represent means ± SE of 14 independent experiments. B: cells were homogenized in TRIzol reagent, and total RNA was extracted and submitted to RT-PCR. Bars express the ratio between leptin and β-actin amplification products. A representative blot of each experiment is depicted at top. Lanes are aligned with the respective column in the graph. Values are means ± SE of 5–6 independent experiments and are expressed as arbitrary units [1 AU = mean value of control (–)]. *P < 0.05 vs. control (–); #P < 0.05 vs. correspondent treatment in the absence of melatonin.](Image)
MT₂ but not MT₁ antagonist blocked the effect of melatonin on insulin-induced leptin release. To determine the involvement of MT₁ or MT₂ melatonin receptor subtypes on melatonin action on leptin release, we assessed the ability of 10 μM luzindole (a nonselective melatonin receptor antagonist) and 10 μM 4P-PDOT (a selective MT₂ receptor antagonist) to antagonize the effect of melatonin on insulin-induced leptin release. 4P-PDOT did not show such an effect, whereas luzindole completely blocked the positive interaction of melatonin and insulin on leptin release. In addition, 4P-PDOT or luzindole alone had no effect on leptin release in control adipocytes (Fig. 6).

Melatonin upregulates insulin-induced IRβ and Akt phosphorylation. To gain further insight into the molecular basis by which melatonin and insulin interact to induce leptin release and mRNA expression, we investigated the insulin-signaling cascade in the presence of melatonin. Figure 7A shows a representative blot of the immunoprecipitated IRβ protein content, which did not present significant differences among the groups. Figure 7B shows that insulin alone induced an expected (61) and significant rise (2.5-fold the control value) in IRβ tyrosine phosphorylation. However, when the adipocytes were treated with insulin plus melatonin, IRβ tyrosine phosphorylation was significantly increased (2.3-fold) compared with insulin alone. To investigate whether the modulation of this early step in insulin cell signaling was transmitted to downstream convergent targets, we accessed Akt serine phosphorylation (Fig. 7B). Similarly, Akt serine phosphorylation was significantly upregulated (2-fold) by the treatment with the two hormones compared with insulin alone.

DISCUSSION

Glucocorticoids and insulin have been proposed as potential upregulators of leptin synthesis. In fact, as demonstrated earlier (8, 18, 20, 54), our results confirmed the ability of glucocorticoids to stimulate leptin gene expression and release. The effect of insulin, however, is more controversial. In humans, many studies (40, 55, 60) have found no acute stimulatory effect, whereas long-lasting hyperinsulinemic clamps resulted in increased serum leptin levels in some (33, 59), but not all (19, 28), studies. Direct effects of insulin on leptin gene expression are also unclear, since increase (54), decrease (18, 52), and no change (27) have been reported. In rodents, insulin has been reported to increase leptin levels (6, 8, 11, 16, 39). However, some authors showed that insulin was effective in stimulating leptin production at very high concentrations (6, 8) or after a long time of stimulation (39). In addition, others reported that insulin at a physiological range has no acute stimulatory effect on leptin secretion from isolated rat adipocytes (16, 39). Our findings demonstrated that insulin by itself had no direct stimulatory effect on leptin expression but inter-

![Fig. 3. Effect of forskolin (FK) on leptin release: dose-response curve in the presence and absence of melatonin. Adipocytes from epididymal fat pads were isolated from male Wistar rats. Cells were incubated at 37°C for 6 h with different concentrations (0.1, 1, 10, 30, and 100 μM) of forskolin in the absence and presence of 1 nM melatonin. Aliquots of the medium were collected for determination of leptin content by RIA. Data represent means ± SE of 3 independent experiments performed in duplicate.](image)

![Fig. 4. Effect of forskolin associated or not with melatonin, insulin, and/or dexamethasone on leptin release (A) and gene expression (B). Isolated adipocytes were incubated at 37°C for 6 h with or without 25 μM forskolin in the absence or presence of 1 nM melatonin and/or 5 nM insulin and/or 7 nM dexamethasone. A: aliquots of the medium were collected for determination of leptin content by RIA. Three sets of experiments are depicted in the graph. On the 1st, cells were treated without forskolin and melatonin; on the 2nd, forskolin was added; and on the last, forskolin and melatonin were used. B: cells were homogenized in TRIzol reagent, and total RNA was extracted and submitted to an RT-PCR reaction. Bars express the ratio between leptin and β-actin amplification products. A representative blot of each experiment is depicted at top. Lanes are aligned with the respective column in the graph. Data are expressed as AU [1 AU = mean value of control (--)j and represent means ± SE of 4–5 independent experiments. *P < 0.05 vs. control (--)j; *P < 0.05 vs. corresponding treatment shown in the 2nd set; *P < 0.05 vs. corresponding treatment in the 1st set; *P < 0.05 vs. the correspondent treatment in the absence of forskolin; *P < 0.05 vs. corresponding treatment in the absence of melatonin.](image)
We have already investigated the interaction between melatonin and insulin, focusing on metabolic responses of adipocytes; melatonin in vitro elicited an enhancement in the adipocyte sensitivity to insulin. In addition, the absence of melatonin as a consequence of pineal ablation decreased insulin-stimulated glucose uptake in adipocytes in both fed (1, 30) and fasted animals (2). During fasting, pinealectomy has also revealed alterations in insulin-stimulated glucose oxidation and incorporation into lipids (2). Taken together, these data and the present study suggest that the response to insulin might be modulated by melatonin, and this interaction not only underlies the metabolic effects but can also be extrapolated to other adipocyte functions, like its ability to produce leptin.

Recent studies have reported contradictory results on the possible relationship between melatonin and leptin secretion. In humans, for example, no major effect was reported in postmenopausal women supplied with melatonin during daytime (10), although a recent work with nocturnal-life style adult humans reported a simultaneous decrease in melatonin and leptin levels (49). Middle-aged rats, together with a decline in melatonin production, displayed higher absolute serum leptin compared with young rats (45, 50, 63). This observation could be attributed to increased aging-related adiposity (48, 62), as circulating leptin is strictly and positively correlated with the amount of body fat (12, 25, 32). However, when adjusted for body fat percentage, leptin levels are, in fact, significantly lower in aged rats (37, 43, 48). Moreover, it was shown that the daily rhythm in serum leptin levels is abolished with aging (48). In this way, it is possible to conclude that the well-known reduction of melatonin production in aged rats might be the cause of the observed reduction in leptin serum levels.

Results that are apparently contradictory were demonstrated when pinealectomy model was adopted. Although melatonin administration suppressed increased leptin levels after pinealectomy (14), a recent study (42) showed no differences in leptin levels between pinealectomized and intact obese rats. We have described that pinealectomy has no influence on plasma leptin levels in fed rats measured at three different times of the day (1) but interacts synergistically with fasting to provoke a more accentuated fall in leptinemia (2). Studies using melatonin supplementation showed both an increase in leptin levels in some mammalian species [Mustella vison (41) and garden dormouse (3)] and a decrease in middle-aged rats [in parallel with body weight reduction (50, 63)].

All of these controversies may be due not only to the use of different species but also to the use of different models in vivo that results in some interferences: 1) changes in glucocorticoid levels [melatonin treatment shows both an increase in leptin production (30) and leptin levels (49)]. Middle-aged rats, together with a decline in leptinemia, are followed by a decrease in hypothalamic-pituitary-adrenal axis activity, resulting in a decrease in glucocorticoid levels. 

Interestingly, a synergism between insulin and dexamethasone show daily rhythms, with maximal plasma concentrations at night (1, 26, 49), when they might interact on the adipose tissue to magnify the daily amplitude of leptin production.

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To clarify the mechanisms on melatonin action, we have shown that melatonin totally prevented the inhibitory effects of forskolin on both leptin synthesis and secretion, suggesting that its action occurs via a negatively coupled adenyl cyclase receptor and cAMP formation. Besides, when adipocytes were treated with PTX (75 mg/ml; which ADP-ribosylates some Gi proteins, thereby uncoupling them from their associated receptors and inhibiting the signaling pathway), the effect of melatonin was completely abolished, reinforcing the hypothesis that melatonin modulates the synthesis and the secretion of leptin through a PTX-sensitive Gi protein-coupled membrane receptor.

As mentioned before, MT1 and MT2 melatonin receptors were recently described in adipocytes. By using a subtype-selective MT2 receptor antagonist (4P-PDOT) and a nonselective receptor antagonist [luzindole (34)], we demonstrated that the effect of melatonin acting synergistically with insulin to induce leptin secretion is an event dependent on MT1 melatonin receptor subtype.

It was recently reported (27) that processes linked to Gi protein stimulation might regulate the release of leptin in adipocytes. Those authors showed that insulin alone was unable to increase leptin release in isolated adipocytes from massively obese human subjects. However, by using GPCR agonists, they demonstrated that insulin induced a twofold increase in leptin secretion from the isolated adipocytes. These events were inhibited by PTX. Therefore, these findings are in agreement with ours, as melatonin is also a Gi protein agonist, and the stimulatory effect of insulin was obtained only in the presence of melatonin. Moreover, it was shown that Gα2 protein improves insulin signaling through the suppression of phosphotyrosine phosphatase 1B (57).

To gain further insight into the molecular basis of the permissive effect of melatonin on insulin-induced leptin expression, we investigated the insulin-signaling pathway after melatonin incubations. Interestingly, our data show that melatonin is able to upregulate insulin-induced IRβ tyrosine phosphorylation without modifying the protein content. This effect seems to be transmitted through the intracellular insulin cascade, since the serine phosphorylation of the downstream Akt seems to be transmitted through the intracellular insulin cascade.

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MELATONIN ACTION ON LEPTIN EXPRESSION

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