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The antimicrobial peptide LL-37 alters human osteoblast Ca^{2+} handling and induces Ca^{2+}-independent apoptosis

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Short title: \textbf{LL-37-induced apoptosis and Ca^{2+} signaling}

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Abstract

The human antimicrobial peptide cathelicidin LL-37 has, besides its antimicrobial properties, also been shown to regulate apoptosis in a cell type specific manner. Mechanisms involved in LL-37-regulated apoptotic signaling are not identified. Here, we show that LL-37 reduces human osteoblast-like MG63 cell number and cell viability in the µM concentration-range with an IC\textsubscript{50} value of about 5 µM. Treatment with 4 µM LL-37 increased the number of Annexin V positive cells and stimulated activation of caspase 3 showing that LL-37 promotes apoptosis. Treatment with 4 µM LL-37 caused an acute and sustained rise in intracellular Ca\textsuperscript{2+} concentration assessed by laser-scanning confocal microscopy of Fluo 4-AM loaded MG63 cells. LL-37 increased Ca\textsuperscript{2+} also in the presence of the respective L and T-type voltage-sensitive Ca\textsuperscript{2+} channel blockers nifedipine and NiCl\textsubscript{2}. LL-37 had no effect on Ca\textsuperscript{2+} in cells incubated with Ca\textsuperscript{2+}-free solution. LL-37 (4 and 8 µM) reduced MG63 cell number both in the presence and absence of Ca\textsuperscript{2+} in the medium. In conclusion, LL-37 reduces osteoblast cell number by promoting apoptosis, and furthermore, LL-37 stimulates Ca\textsuperscript{2+} inflow via a mechanism independent of voltage-sensitive Ca\textsuperscript{2+} channels. Interestingly, LL-37-induced lowering of cell number seems to be mediated via a mechanism independent of Ca\textsuperscript{2+}.

**Key words:** Annexin V; Apoptosis; Calcium; Caspase 3; LL-37; Osteoblast
The human antimicrobial peptide cathelicidin LL-37 is stored as the proprotein form hCAP-18 in neutrophils and epithelial cells until activated by the serine protease proteinase 3 and subsequently released [1, 2]. LL-37 is an amphiphilic α-helical cationic peptide possessing hydrophobic as well as hydrophilic properties [3]. LL-37 exerts a direct antimicrobial activity through disrupting the cell wall of both gram-negative and gram-positive bacteria causing bacterial cell lysis and by neutralizing lipopolysaccharide [4-6]. The cationic LL-37 molecule binds to negatively charged microbial membrane lipids thereby showing membrane selectivity [3]. Furthermore, LL-37 potentiates chemokine production by microbial stimuli in keratinocytes and other epithelial cells, suggesting that it enhances the immune defense of the skin [7].

LL-37 has, besides its antimicrobial and immune modulator activities, also been shown to affect various cellular functions, such as phagocytosis [8], cell differentiation [9] and apoptosis [10-16]. Importantly, the effects of LL-37 on apoptosis seem to be cell type specific; LL-37 promotes apoptosis in vascular smooth muscle cells [10], periodontal ligament cells [11], neutrophils [12], T cells [13] and airway epithelium [14] but suppresses apoptosis in keratinocytes [15] and dermal fibroblasts [16]. For neutrophils, LL-37 has been reported to exert both pro- and anti-apoptotic effects [12, 17].

In periodontitis, which is a progressive inflammatory disease, the end-stage is characterized by destruction of the alveolar bone leading to loss of teeth. Interestingly, the LL-37
concentrations are high (µM) in the gingival crevicular fluid from patients suffering from chronic periodontitis [18], suggesting that this peptide may influence the disease process. The bone forming osteoblasts represent a very important cell type in both periodontal health and disease responsible for maintaining the alveolar bone mass [19].

The signaling pathways and mechanisms involved in LL-37 regulated apoptosis are not completely understood [3]. The Ca^{2+} ion is thought to play a role in cell killing and apoptosis and dysfunctional regulation of Ca^{2+} homeostasis can result in apoptosis [20, 21], suggesting that Ca^{2+} may be involved in LL-37-induced pro-apoptotic signaling. LL-37 has been reported to interact with different cellular proteins such as the purinergic P2X_7 receptor [17, 22] and the epidermal growth factor receptor [23-25], but LL-37 interacts also with DNA [26]. In the present study, we investigate effects of LL-37 on human osteoblast-like MG63 cell viability and Ca^{2+} signaling demonstrating that LL-37 induces apoptosis also in this cell type. Additionally, we demonstrate that LL-37 causes a rapid and sustained rise in the intracellular Ca^{2+} concentration through inflow of Ca^{2+} from the extracellular space, suggesting that LL-37 alters Ca^{2+} handling. Interestingly, the LL-37-induced attenuation of osteoblast cell number and cell viability seems to be mediated through a mechanism independent of Ca^{2+}. 
Materials and methods

Cell culture and experimental procedure

The human osteoblast-like MG63 cell line and the primary human osteoblast cell line hFOB 1.19 from American Type Tissue Culture Collection (ATCC, Manassas, VA, USA) were cultured in DMEM/Ham’s F12 (1:1) cell culture medium (Life Technologies, Invitrogen, Carlsbad, CA, USA) supplemented with antibiotics (penicillin 50 U/ml, streptomycin 50 µg/ml) and 10% fetal calf serum in accordance with instructions from ATCC. The cells were kept in a water-jacketed cell incubator at 37 °C under 5% CO₂ in air. The MG63 cells express markers for osteogenic differentiation such as alkaline phosphatase (ALP) enzyme activity and form mineralized nodules showing that they are representative for native osteoblasts [27, 28]. The cells were trypsinized (0.25% trypsin/EDTA) and reseeded upon reaching confluence. Medium was exchanged every second day. Experiments were performed on sub-confluent cells (80% confluence). The cells were used for experiments in passages 3-10. Incubation with LL-37 caused similar effects irrespective of passage number. Before experiments fetal calf serum was omitted in order to standardize the experimental conditions. For experiments assessing the importance of Ca²⁺ for LL-37-induced effects on cell number, MG63 cells were incubated in either DMEM cell culture medium containing 1.8 mM Ca²⁺ or Ca²⁺-free DMEM medium, both from Life Technologies. The Ca²⁺-free DMEM medium was further supplemented with 1.8 mM MgCl₂ to achieve iso-osmolar conditions and to supplement with divalent cations to compensate for those lost by the omission of Ca²⁺. In order to achieve culture conditions with low Ca²⁺ concentration, the Ca²⁺ containing DMEM medium was supplemented with 1.8 mM of the Ca²⁺ chelator ethylene glycol-bis(β-
aminoethyl ether)-N,N,N’,N’-tetraacetic acid (EGTA, Sigma Chemicals, St Louis, MO, USA).

Assessment of cell number and cell viability

Number of cells was calculated in a Bürker chamber as appropriate. Cell viability was assessed using trypan blue exclusion test. The cells were incubated for 2 min with 0.4% trypan blue (Sigma) and then washed three times in 0.9% NaCl. Cells containing trypan blue was counted as a measure of dead/dying cells. Cell morphology was assessed in digital photographs from a Nikon TMS microscope equipped with digital camera (Pixelink, Nikon, Nikon Nordic AB, Solna, Sweden).

Determination of active caspase 3

After washing in phosphate buffered saline (PBS), cellular proteins were extracted using a protein extraction buffer provided in the active caspase 3 (aCasp-3) ELISA kit from R&D (R&D Systems, Minneapolis, MN, USA). The amount of active caspase 3 was determined by ELISA according to manufacturer’s instructions, and normalized to total protein in each sample measured by a Bio-Rad protein assay kit (BioRad, Hercules, CA, USA). Each sample was analyzed in duplicate.

Annexin V flow cytometry

Apoptosis was assessed by flow cytometry using Annexin V staining. Cells were washed with PBS and then incubated with FITC-labeled Annexin V and the fluorescent viability dye 7-
aminoactinomycin D (7-AAD) using FITC Annexin V apoptosis detection kit 1 (BD, Franklin Lakes, NJ, USA) according to manufacturer’s instructions. The proportion of Annexin V positive/negative and 7-AAD positive/negative cells was determined by flow cytometry using an Accuri C6 flow cytometer (BD). Cells in early stages of apoptosis are Annexin V positive and 7-AAD negative, whereas cells in later stages of apoptosis and necrosis stain positive for both Annexin V and 7-AAD. Gates for Annexin V and 7-AAD positive cells were set using fluorescence minus one control. 20 000 events were recorded in each sample.

**Measurement of intracellular Ca\(^{2+}\) concentration**

For determination of intracellular Ca\(^{2+}\) concentration, the cells were cultured on glass bottom cell culture Petri dishes (MatTek, Ashland, MA, USA). The cells were washed with PBS, incubated with the Ca\(^{2+}\) sensitive fluorescent dye Fluo 4-AM (3 µM, Invitrogen) for 40 min at room temperature, and then washed carefully. During the Ca\(^{2+}\) measurements the cells were incubated in a HEPES buffered salt solution containing 2.5 mM Ca\(^{2+}\). This Ca\(^{2+}\) concentration is somewhat higher than the plasma concentration of Ca\(^{2+}\) in healthy adults. We used HEPES buffered salt solution with 2.5 mM Ca\(^{2+}\) only in these acute experiments. The composition of the HEPES buffered salt solution was (mM): NaCl 135.5, KCl 5.9, CaCl\(_2\) 2.5, MgCl\(_2\) 1.2, N-2-hydroxyethylpiperazine-\(N’\)-2-ethanesulfonic acid (HEPES) 11.6 and glucose 11.5. In some experiments measurement of Ca\(^{2+}\) was performed under Ca\(^{2+}\)-free conditions, i.e. in HEPES buffered salt solution without CaCl\(_2\) and with addition of 2 mM EGTA (Sigma). The experiments were performed at room temperature. Fluorescence was recorded using a laser-scanning confocal microscope (LSM 510 PASCAL, Carl Zeiss AG, Göttingen, Germany). The excitation and emission wavelengths were 488 and 505 nm, respectively. The Ca\(^{2+}\) measurements were performed on sub-confluent (80% confluence) cells as an integrated
signal from all cells (about 300 cells) within the visual field at x100 magnification. The confocal pinhole setting was kept identical for all experiments.

**Drugs**

LL-37 was purchased from Bachem AG (Bubendorf, Switzerland) and dissolved in dimethyl sulfoxide (DMSO) according to manufacturer’s instructions. The L-type Ca$^{2+}$ channel blocker nifedipine (Sigma), the thromboxane A2 analogue U46619 (Tocris Bioscience, Bristol, United Kingdom) and the P2X$_7$ receptor antagonist AZ 11645373 (Tocris) were dissolved in DMSO. The controls received vehicle, DMSO, as appropriate. The final concentration of DMSO was 0.1%.

**Statistics**

Values are presented as means ± S.E.M. Statistical significance was calculated using ANOVA and Student’s two-tailed t-test for unpaired comparisons with Bonferroni correction for post hoc analysis as appropriate. P values less than 0.05 were regarded to denote statistical significance.
Results

**LL-37 attenuates MG63 cell number and cell viability**

Treatment with LL-37 for 24 h reduced the number of human MG63 osteoblasts by 40 and 75% at 4 and 8 µM, respectively (Fig. 1a). Lower concentrations of LL-37 (0.1-2 µM) had no effect on the number of cells (Fig. 1a). LL-37 caused a concentration-dependent decrease in cell number with an IC₅₀ value of about 5 µM. Treatment with 4 µM LL-37 for 1 and 3 days reduced MG63 cell number by about 40% (Fig. 1b). A lower concentration (0.1 µM) of LL-37 had no effect on cell number neither at 1 nor 3 days of treatment (Fig. 1b). Staining with trypan blue, assessing cell viability, showed that treatment with LL-37 (8 µM) for 24 h reduced cell number and caused alteration of cell morphology characterized by shrinkage of the cells representing classical signs of apoptosis (Fig. 2). Furthermore, almost all cells remaining after treatment with 8 µM LL-37 contained trypan blue indicating that they represent dead/dying cells (Fig. 2). No trypan blue positive cells were observed in response to a lower concentration (1 µM) of LL-37 (Fig. 2). The positive trypan blue staining observed in response to 8 µM LL-37 in MG63 cells was confirmed also in another human osteoblast cell line, hFOB 1.19 cells (Fig. 3), demonstrating that µM concentrations of LL-37 reduce cell viability in two different human osteoblast cell lines.

**LL-37 increases the number of Annexin V positive cells and elevates active caspase 3 in MG63 cells**

Treatment with LL-37 (4 µM) for 6 h increased the proportion of Annexin V positive MG63 cells by about 70% demonstrated by flow cytometry (Fig. 4a). The well-known pro-apoptotic
agent staurosporine (0.5 µM) was included as a positive control [29]. Treatment with 0.5 µM staurosporine for 6 h increased the number of Annexin V positive cells by about 9 times (Fig. 4a). Staurosporine (0.5 µM) but not LL-37 (4 µM) increased the proportion of Annexin V positive cells also at a shorter time-point, i.e. 2 h (Fig. 4a). Stimulation with LL-37 (4 µM) for 24 h increased the amount of active caspase 3 between 2 and 3 times in MG63 cells (Fig. 4b). The positive control staurosporine (0.5 µM) increased active caspase 3 by about 2-fold (Fig. 4b). Taken together these data show that LL-37 is pro-apoptotic for osteoblasts.

**LL-37 increases MG63 intracellular Ca^{2+} concentration**

Defective cellular Ca^{2+} handling is thought to be involved in pro-apoptotic signaling [21], and therefore we assessed the effects of LL-37 on the intracellular Ca^{2+} concentration. Treatment with LL-37 (4 µM) caused an acute (within about 60 s) and sustained rise in intracellular Ca^{2+} concentration demonstrated by laser-scanning confocal microscopy of Fluo 4-AM labeled MG63 cells incubated in Ca^{2+} containing (2.5 mM) HEPES-buffered salt solution (Figs. 5a and b). A lower concentration of LL-37 (0.4 µM) also elevated Ca^{2+} but the Ca^{2+} response to 0.4 µM LL-37 was small compared to that of 4 µM (Fig. 5b). Addition of vehicle control (0.1% DMSO) had no effect on Ca^{2+} (Fig. 5a). LL-37 (0.4 and 4 µM) had no effect on intracellular Ca^{2+} concentration in Ca^{2+}-free solution (Fig. 5c), suggesting that the LL-37-induced increase in Ca^{2+} depends on inflow of extracellular Ca^{2+}. Treatment with 100 nM and 1 µM of the L-type voltage-sensitive Ca^{2+} channel blocker nifedipine had no effect on the LL-37-induced Ca^{2+} response (4 µM LL-37), suggesting that LL-37 acts via another mechanism than by stimulation of Ca^{2+} inflow through L-type Ca^{2+} channels (Figs. 6 and 7a). The T-type Ca^{2+} channel blocker NiCl_{2} (100 µM) had no effect on the LL-37-induced (4 µM) Ca^{2+} response (Fig. 7b), suggesting that inflow of Ca^{2+} by LL-37 is mediated through another
pathway than via T-type Ca\(^{2+}\) channels. Furthermore, inclusion of the P2X\(_7\) receptor antagonist AZ 11645373 (10 µM) had no impact on the rise in Ca\(^{2+}\) evoked by 4 µM LL-37 (Fig. 7c). The thromboxane A2 analogue U46619 was included as positive control causing a rapid and powerful rise in intracellular Ca\(^{2+}\) concentration (Fig. 7d).

*LL-37 reduces MG63 cell number both in the presence and absence of extracellular Ca\(^{2+}\)*

Treatment with LL-37 (8 µM) for 24 h reduced the number of MG63 cells by about 55% for cells cultured in DMEM culture medium containing 1.8 mM Ca\(^{2+}\) and by about 85% for cells cultured in Ca\(^{2+}\)-free DMEM culture medium (Fig. 8a). In fact, the LL-37-induced reduction of cell number was more powerful (P<0.01) in the absence than in the presence of extracellular Ca\(^{2+}\) (Fig. 8a). A lower concentration of LL-37 (4 µM) reduced cell number by about 15% in the presence (86 ± 2% for LL-37-treated cells vs. 100 ± 5% for control cells, P<0.05, n=3 in each group) and by about 35% in the absence (66 ± 7% for LL-37-treated cells vs. 100 ± 16% for control cells, P<0.05, n=3 in each group) of extracellular Ca\(^{2+}\). Omitting Ca\(^{2+}\) for 24 h reduced slightly, but not significantly, the number of cells as demonstrated when cell-counts are plotted as absolute data (Fig. 8b). The MG63 cells showed similar morphology in the presence and absence of Ca\(^{2+}\) (Fig. 8c). Treatment with LL-37 (4 µM) for 24 h attenuated cell number by about 60% when the Ca\(^{2+}\) chelator agent EGTA (1.8 mM) was included in the Ca\(^{2+}\)-containing DMEM culture medium in order to lower Ca\(^{2+}\) (Fig. 9). LL-37 (4 µM) reduced cell number by about 60% also when extra Ca\(^{2+}\) (final Ca\(^{2+}\) concentration 3.6 mM) was included in the EGTA containing medium (Fig. 9). For these experiments EGTA was administered in an equimolar concentration to extracellular Ca\(^{2+}\) (1.8 mM) in order to bind most of the Ca\(^{2+}\) ions. Thus, LL-37-induced lowering of osteoblast cell number is
observed both when the cells are cultured under Ca\textsuperscript{2+}-free conditions and when Ca\textsuperscript{2+} ions are absorbed with EGTA.
Discussion

In the present study, we demonstrate that the human antimicrobial peptide LL-37 induces apoptosis in human osteoblast-like MG63 cells and that this effect is associated with elevated intracellular Ca\(^{2+}\) concentration. LL-37 causes, in the \(\mu\)M concentration range, an acute and sustained rise in intracellular Ca\(^{2+}\) in Ca\(^{2+}\)-containing but not in Ca\(^{2+}\)-free solution showing that the LL-37-induced increase in intracellular Ca\(^{2+}\) is due to an inflow of Ca\(^{2+}\) along its gradient from the extracellular space to the cytosol. The increase in Ca\(^{2+}\) by LL-37 was much stronger at 4 than at 0.4 \(\mu\)M, suggesting a concentration-dependent effect, although it is difficult to conclude firmly the concentration-dependence since we have investigated only two concentrations of LL-37. Membrane depolarization results in an inflow of Ca\(^{2+}\) from the extracellular space causing a sustained and long-lasting increase in intracellular Ca\(^{2+}\) [30] similar to that observed in response to LL-37 in the present study. The pattern of LL-37-induced rise in intracellular Ca\(^{2+}\) concentration is thus compatible with inflow of Ca\(^{2+}\) from the extracellular space. Osteoblasts (MC3T3-E1 cells and MG63 cells) have been reported to express voltage-sensitive Ca\(^{2+}\) channels [31, 32]. Our data show that neither the L-type Ca\(^{2+}\) channel blocker nifedipine nor the T-type Ca\(^{2+}\) channel blocker NiCl\(_2\) have impact on the LL-37 evoked rise in Ca\(^{2+}\) in MG63 cells, suggesting that the inflow of Ca\(^{2+}\) triggered by LL-37 is through another mechanism than via voltage-sensitive L-type and T-type Ca\(^{2+}\) channels. We used relevant concentrations of nifedipine (0.1 and 1 \(\mu\)M), which fully inhibit inflow of Ca\(^{2+}\) via L-type Ca\(^{2+}\)channels in cultured vascular smooth muscle cells [30], and NiCl\(_2\) (100 \(\mu\)M) inhibiting T-type but not L-type Ca\(^{2+}\) channels [33]. Furthermore, inclusion of the selective and highly potent P2X\(_7\) receptor antagonist AZ 11645373 [34] had no effect on the rise in Ca\(^{2+}\) evoked by LL-37, suggesting an alternative mechanism. Based on our findings presented
here, we suggest that the LL-37-induced inflow of extracellular Ca$^{2+}$ represents a novel signaling pathway for LL-37 that may involve LL-37-induced permeabilization of the cell-membrane causing formation of trans-membrane pores and/or that LL-37 acts as a detergent. These data implicate that LL-37 may work through a similar mechanism in human osteoblasts as in LL-37-induced permeabilization of the bacterial cell wall [3].

Here, we show for the first time that the antimicrobial peptide LL-37 reduces human MG63 osteoblast cell number by promoting apoptosis. LL-37-induced apoptosis was demonstrated by both enhanced proportion of Annexin V positive cells and by elevated active caspase 3 level in response to LL-37-treatment. Furthermore, LL-37-treated cells showed altered morphology such as cell shrinkage representing a classical sign of apoptosis. Previously, pro-apoptotic effects of LL-37 have been demonstrated in vascular smooth muscle cells, periodontal ligament cells, neutrophils, T cells and airway epithelial cells [10-14]. We demonstrate reduction of osteoblast cell number by LL-37 in the µM concentration-range, while no effect on cell number is observed at lower concentrations of LL-37. We have previously shown that LL-37 reduces lipopolysaccharide-induced MCP-1 and IL-6 expression at low concentrations (0.1 and 1 µM) and induces apoptosis only at high (>5 µM) concentrations in human periodontal ligament cells [11]. LL-37-induced pro-apoptosis is thus observed in different cell systems but only in the µM concentration-range. Very high levels of LL-37 have been demonstrated in lesional tissue from patients suffering from autoimmune diseases such as psoriasis, rosacea and ulcerative colitis [35-37]. For example, the median concentration of LL-37 is 304 µM in psoriatic skin lesions [35]. The LL-37 levels are elevated locally in chronic periodontitis, in fact they are well within the µM concentration-range [18], suggesting that LL-37-induced apoptosis of osteoblasts may have impact on alveolar bone
homeostasis in patients suffering from this disease. Thus, we may conclude that the LL-37-induced apoptosis of osteoblasts, observed in the µM concentration-range in the present study, is relevant for the in-vivo situation considering the very high levels of LL-37 observed in various autoimmune and inflammatory diseases.

Ca\(^{2+}\) governs many important cellular processes and is thought to be involved in apoptosis [21, 38]. A rise in intracellular Ca\(^{2+}\) may originate from intracellular stores such as the endoplasmic reticulum, but also from the extracellular space [21]. Here, we show that LL-37 elevates intracellular Ca\(^{2+}\) concentration in human MG63 osteoblasts through stimulation of Ca\(^{2+}\) inflow. The LL-37 evoked inflow of Ca\(^{2+}\) seems not to be critically important for the LL-37-induced attenuation of MG63 cell number, since LL-37 lowers cell number both in the presence and absence of Ca\(^{2+}\) in the cell culture medium and furthermore, LL-37 causes a rise in intracellular Ca\(^{2+}\) but no apoptosis at a low concentration (0.4 µM). Ca\(^{2+}\)-independent apoptosis has been described in different experimental systems [39, 40]. Interestingly, the LL-37 evoked inward flow of Ca\(^{2+}\), occurring independent of LL-37-induced apoptosis, may represent an important mechanism regulating Ca\(^{2+}\)-dependent cellular processes governed by LL-37. Thus, we demonstrate here that LL-37 alters human osteoblast Ca\(^{2+}\) handling and induces Ca\(^{2+}\)-independent apoptosis.

In summary, we show that LL-37 alters cellular Ca\(^{2+}\) homeostasis by causing stimulation of Ca\(^{2+}\) inflow through a voltage-sensitive L- and T-type Ca\(^{2+}\) channel independent mechanism in human osteoblasts. Furthermore, we demonstrate that LL-37 induces apoptosis of osteoblasts via a mechanism that is independent of Ca\(^{2+}\).
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References


29 Dezaki K, Maeno E, Sato K, Akita T, Okada Y: Early-phase occurrence of K+ and Cl-efflux in addition to Ca 2+ mobilization is a prerequisite to apoptosis in HeLa cells. Apoptosis 2012;17:821-831.


Figure legends

**Fig. 1.** (a) Treatment with LL-37 for 24 h reduces MG63 osteoblast cell number in a concentration-dependent manner. LL-37 at 4 and 8 µM reduces osteoblast cell number by 40 and 75%, respectively, while lower concentrations of LL-37 lack effect. (b) Treatment with 4 µM LL-37 for 1 and 3 days reduces MG63 cell number by about 40%. A lower concentration (0.1 µM) of LL-37 has no effect on cell number neither at 1 nor 3 days of treatment. Values are means ± SEM of 4-15 observations in each group. *, ** and *** represent P<0.05, P<0.01 and P<0.001, respectively, compared to controls (ctrl).

**Fig. 2.** Staining with trypan blue, assessing cell viability, shows that treatment with 8 µM LL-37 for 24 h reduces MG63 cell number and causes alteration of cell morphology characterized by shrinkage of the cells. Furthermore, nearly all LL-37-treated cells contain trypan blue indicating that these cells represent dead/dying cells. No trypan blue positive cells were observed in response to a lower concentration (1 µM) of LL-37. Control cells (ctrl) show normal morphology with no trypan blue positive cells. Bars represent 25 µm.

**Fig. 3.** Treatment with LL-37 (8 µM) for 24 h causes accumulation of trypan blue in primary human osteoblast hFOB 1.19 cells. Control cells (ctrl) show no trypan blue positive cells. Trypan blue positive cells represent dead/dying cells. Bars represent 20 µm.
Fig. 4. (a) Treatment with 4 µM LL-37 for 6 h increases the proportion of apoptotic MG63 cells. Apoptosis was determined by flow cytometric analysis of Annexin V positive cells. Staurosporine (0.5 µM) was included as positive control. (b) Treatment with 4 µM LL-37 for 24 h increases MG63 cellular active caspase 3 (aCasp-3) level 2 to 3 times. The amount of aCasp-3 was determined by ELISA and normalized to total protein in each sample. Values are means ± SEM of 3-4 observations in each group. *, ** and *** represent P<0.05, P<0.01 and P<0.001, respectively, compared to controls (ctrl). N.S. = not significant.

Fig. 5. (a) Treatment with LL-37 (4 µM) causes an acute and sustained rise in intracellular Ca\(^{2+}\) concentration assessed by laser-scanning confocal microscopy of Fluo 4-AM loaded MG63 cells incubated in Ca\(^{2+}\) containing (2.5 mM) HEPES-buffered salt solution. No treatment (left panel) represents the Ca\(^{2+}\) signal in the presence of vehicle control (0.1% DMSO). Addition of 0.1% DMSO has no effect on Ca\(^{2+}\). The Ca\(^{2+}\) indicator Fluo 4-AM fluorescence is shown in red. (b) Line trace showing that both 0.4 and 4 µM LL-37 elevates Ca\(^{2+}\). (c) LL-37 (0.4 and 4 µM) has no effect on intracellular Ca\(^{2+}\) concentration in Ca\(^{2+}\)-free solution. Ca\(^{2+}\)-free conditions were achieved by removing CaCl\(_2\) from the HEPES-buffered salt solution and by inclusion of 2 mM EGTA. Each experiment was repeated at least twice.

Fig. 6. LL-37 (4 µM) increases MG63 intracellular Ca\(^{2+}\) concentration monitored by laser-scanning confocal microscopy of Fluo 4-AM loaded cells in the presence of L-type Ca\(^{2+}\) channel blocker nifedipine (100 nM). Nifedipine was included at the arrow and present throughout the experiment. This trace shows one representative experiment out of two.
Fig. 7. Treatment with (a) 1 µM nifedipine, (b) 100 µM NiCl₂ and (c) 10 µM AZ11645373 has no effect on the LL-37-induced (4 µM) Ca²⁺ response in MG63 cells. (d) The thromboxane A2 analogue U46619 (10 µM) was included as positive control causing a rapid and powerful rise in intracellular Ca²⁺ concentration. The intracellular Ca²⁺ concentration was monitored by laser-scanning confocal microscopy of Fluo 4-AM loaded MG63 cells. Nifedipine, NiCl₂ and AZ11645373 were included at the arrow and present throughout the experiment. Each experiment was repeated at least twice.

Fig. 8. (a) Treatment with 8 µM LL-37 for 24 h reduces MG63 cell number by about 55% for cells cultured in DMEM culture medium containing 1.8 mM Ca²⁺ and by 85% for cells cultured in Ca²⁺-free DMEM culture medium. (b) Omitting Ca²⁺ for 24 h reduces slightly, but not significantly, the number of cells as demonstrated when cell-count data are plotted as absolute data. (c) The MG63 cells show similar morphology in the presence and absence of Ca²⁺. Bars in panel c represent 20 µm. Values are means ± SEM of 4-5 observations in each group. * and *** represent P<0.05 and P<0.001 compared to controls (ctrl) and ** represents P<0.01 for LL-37-treated groups as indicated.

Fig. 9. Treatment with 4 µM LL-37 for 24 h reduces cell number by about 60% for cells grown in culture medium (DMEM + 1.8 mM Ca²⁺) containing either 1.8 mM EGTA alone or 1.8 mM EGTA in combination with Ca²⁺ in excess (3.6 mM Ca²⁺). Values are means ± SEM of 3 observations in each group. ** represents P<0.01 compared to controls (ctrl).
Fig. 1

(a) Bar graph showing cell number (% of control) across different concentrations of LL-37 (μM).

(b) Line graph illustrating cell number (% of control) over time (days) for different treatments.
Fig. 2
Fig. 3
Fig. 4

(a) Apoptotic cells (% of control) over time:
- ctrl
- 4 μM LL-37
- 0.5 μM staurosporine

(b) aCasp-3 (% of control):
- 2 h
- 6 h

Significance levels:
- N.S.
- * p < 0.05
- ** p < 0.01
- *** p < 0.001
Fig. 5

(a) Confocal images of No treatment (left) and 4 μM LL-37 (right) showing cell morphology.

(b) Graph showing intracellular [Ca\(^{2+}\)] behavior over time with arrows indicating additions of 0.4 μM and 4 μM LL-37.

(c) Graph showing intracellular [Ca\(^{2+}\)] behavior over time with arrows indicating additions of 0.4 μM and 4 μM LL-37.
Fig. 6

Intracellular \([\text{Ca}^{2+}]\) (arbitrary units)

Time (s)

100 nM Nifedipine

4 \(\mu\text{M LL-37}\)
Fig. 7

(a) Intracellular [Ca²⁺] (arbitrary units)

- 1 μM Nifedipine
- 4 μM LL-37

(b) Intracellular [Ca²⁺] (arbitrary units)

- 100 μM NiCl₂
- 4 μM LL-37

(c) Intracellular [Ca²⁺] (arbitrary units)

- 10 μM AZ11545373
- 4 μM LL-37

(d) Intracellular [Ca²⁺] (arbitrary units)

- 10 μM UA66119
Fig. 8

(a) Cell number (% of control) for different conditions with LL-37 (8 μM) compared to control (ctrl) at 1.8 mM Ca^{2+} and 0 mM Ca^{2+}.

(b) Number of cells (cells/m) comparison between control (ctrl) and LL-37 (8 μM) at 1.8 mM Ca^{2+} and 0 mM Ca^{2+}.

(c) Microscopic images showing the cell morphology at 1.8 mM Ca^{2+} and 0 mM Ca^{2+}.
Fig. 9