AGGREGATION OF PLATELETS, PROLIFERATION OF ENDOTHELIAL CELLS AND MOTILITY OF CANCER CELLS ARE MEDIATED BY THE Bβ1(15)-42 RESIDUE OF FIBRIN(OGEN)

Y. M. STOHNII[1], M. V. RYZHYKOVA[1], A. V. REBRIEV[1],
M. D. KUCHMA[2], R. Y. MARUNYCH[1], V. O. CHERNYSHENKO[1✉],
V. A. SHABLII[2], N. M. LYPOVA[3], O. Yu. SLOMINSKYI[1],
L. V. GARMANCHUK[4], T. M. PLATONOVA[1], S. V. KOMISARENKO[1]

[1]Palladin Institute of Biochemistry, National Academy
of Sciences of Ukraine, Kyiv, Ukraine;
[2]Institute of Cell Therapy, Kyiv, Ukraine;
[3]University of Louisville, USA;
[4]ESC "Institute of Biology and Medicine",
Taras Shevchenko National University of Kyiv, Ukraine;
✉e-mail: bio.cherv@gmail.com

The fibrinogen molecule contains multiple binding motifs for different types of cellular receptors, acting as a molecular link between coagulation and cell adhesion. In this study we generated a truncated form of the fibrinogen molecule lacking the Bβ1-42 sequence by site-specific proteolysis and evaluated the role of the fragment in adhesive capabilities of platelets, endothelial and cancer cells. Fibrinogen with the removed Bβ1-42 sequence and fibrin without the Bβ15-42 fragment (desβ1-42 fibrinogen and desABβ15-42 fibrin) were obtained by proteolysis using the specific protease from the venom of Echis multisquamatis. The cleaved fragment was purified by HPLC and was identified using MALDI-TOF. ADP- and collagen-induced aggregation of washed platelets in the presence of fibrinogen desBβ1-42 was studied using an aggregometer. Proliferation of mice aortic endothelial cells (MAEC) and human umbilical vein endothelial cells (HUVEC) was studied using the fibrin desABβ15-42 as the scaffold. Cell viability was quantified by the MTT test (MAEC). Generation time was calculated for the estimation of proliferative activity of HUVEC. Lung cancer cell line H1299 was used to evaluate cancer cell motility in vitro using the scratch assay. Direct comparison of cellular behavior in the presence of truncated vs native forms demonstrated attenuated cell adhesion in the presence of fibrinogen desBβ1-42 and fibrin desBβ15-42. The platelet aggregation rate was only slightly decreased in the presence of fibrinogen desBβ1-42 but resulted in 15-20% disaggregation of adhered platelets. We also observed the substantial decrease of generation time of HUVEC and inhibition of viability of MAEC cells grown on scaffolds of a desABβ15-42 matrix. Finally, desBβ1-42 modulated the motility of H1299 cells in vitro and suppressed the wound healing by 20% compared to the full-length fibrinogen. We postulate that fragment 1-42 of the BβN-domain of fibrinogen is not sufficient for platelet aggregation, however it may contribute to platelet clot formation in later stages. At the same time, this fragment may be important for establishing proper cell-to-cell contacts and cell viability of endothelial cells. Also, 1-42 amino acid fragment of the BβN-domain supported the migration of cancer cells suggesting that interactions of fibrinogen with cancer cells could be a target for anticancer therapy. The Bβ1-42 fragment of fibrinogen contributes to efficient intracellular interactions of different types of cells, including platelets, endothelial cells and cancer cells.

K e y w o r d s: fibrinogen, adhesion, cell migration, endothelium, cell proliferation, platelets.

Introduction

Fibrinogen is a large glycoprotein composed of three pairs of polypeptide chains bound by disulfide bonds into the complex structure represented by two peripheral D-regions, central E-region and flexible αC-region [1]. The amino acid composition of the whole fibrinogen molecule is Aα1-610, Bβ1-461 and γl-411. Each chain is presented in duplicate.

Because of its size and high concentration in blood plasma (2-3 mg/ml) fibrinogen can modulate various physiological processes apart from blood coagulation. In particular it can interact with various biological surfaces, binding non-specifically to glycocalyx and specifically to biological membranes mainly through integrin receptors. The fibrinogen molecule contains several active sites that can interact with cellular integrins, most of them were studied as ligands of platelet integrin IIbIIIa. The first of these are the C-terminal polypeptides of both γ-chains (γ400-411) and RGD-residues of the Aα-chains (α95-98, α572-574) [2, 3]. Another site that is important in fibrinogen interactions with IIbIIIa is the fragment γ312-324 that is hidden in the fibrinogen molecule and exposed after its conversion to fibrin [4]. An important feature of fibrinogen binding to platelets is the role of platelet activation in this process. Fibrinogen cannot bind to non-activated platelets and interacts only with stimulated cells [5].

Among other parts of the fibrinogen molecule, the BβN-domains (Bβ1-60) are supposed to interact with platelets [6]. In particular, peptides that are structural analogues of Bβ15-42 residues of fibrinogen were shown to inhibit platelet aggregation [7]. These residues are also important for the spreading of platelets [8] but their role in platelet adhesion and aggregation is rather controversial.

At the same time, Bβ15-42 residues of BβN-domains can directly bind to VE-cadherin of endothelial cells (EC) [9, 10]. This finding was confirmed in several studies and is supposed to be an important mechanism of the stabilization of the endothelial monolayer during inflammation [11, 12]. Another site of EC interactions with fibrinogen are very low-density lipoprotein receptors (VLDLR).

They also occur through Bβ15-42 residues but have a rather regulatory role not contributing to the stability of interactions [13, 14].

EC as well as numerous other cells were shown to interact with the fibrinogen residue γ117-133 through intracellular adhesion molecule type 1 (ICAM-1) receptors [15]. Among other cells interacting with fibrinogen in an ICAM-1 dependent manner are leucocytes [16] and various types of cancer cells.

Fibrinogen is a component of the extracellular matrix and can regulate cancerogenesis and metastasis [17]. Binding to fibrinogen through ICAM-1 was shown for several types of cancer cells [18, 19]. Several studies indicate a regulatory role of this kind of interaction [20].

Here we would like to emphasize that different parts of the fibrinogen molecule can interact with cellular receptors more or less specifically, sometimes regulating the activity of different types of cells. Identification of the sites of fibrinogen that are important for molecular recognition provides not only information about mechanisms of cellular adhesion, but can also aid in the detection of targets for modulation of such important biological processes as thrombosis, atherogenesis or cancerogenesis.

In this work we focused on BβN-domains of fibrinogen by studying their role in intracellular interactions of platelets, EC and cancer cells (lung cancer line H1299). To achieve this goal we removed the Bβ1-42 peptide of the fibrinogen molecule using a specific protease and studied the changes in behavior of cells that interacted with this truncated form of fibrinogen. We studied aggregation of platelets, proliferation of EC and migration of cancer cells.

Materials and Methods

Fibrinogen. Fibrinogen was purified from blood plasma of healthy donors by the method of Belitser & Varetska, its purity and clottability were controlled as previously described [21]. The procedure of blood collection was performed under the license of National Military Medical Clinical Center "Main Military Clinical Hospital" (Kyiv, Ukraine).

Abbreviations: EC – endothelial cells; VLDLR – very low density lipoprotein receptors; ICAM-1 – intracellular adhesion molecule type 1; HUVEC – human umbilical vein endothelial cells; MAEC – mouse aortic endothelial cells; TBS – 0.05 M Tris-HCl buffer of pH 7.4 with 0.13 M NaCl; ADP – adenosine diphosphate; MTT – 3-(4, 5-diethylthiazoly-2-yl)-2,5-diphenyltetrazolium bromide; FBS – fetal bovine serum, BSA – bovine serum albumin; DMEM – Dulbecco's Modified Eagle's medium; FGF – fibroblast growth factor.

Monomeric fibrin desA and desAB. Fibrin desA and desAB were prepared from human fibrinogen. Fibrin polymerization was initiated by 0.75 NIH/ml thrombin-like enzyme from the venom of *Agkistrodon halys halys* for fibrin desA and 0.5 NIH/ml thrombin for fibrin desAB [22]. In the case of fibrin desAB, 0.1 ml of 40 mM monoiodacetic acid was added to the sample to avoid fibrin cross-linking. Each mixture was incubated for 30 min at 37 °C. The fully formed clot was removed from the incubation mixture by a glass stick, washed and re-dissolved in 0.125% acetic acid.

The truncated form of monomeric fibrin desA was prepared from human fibrinogen that was truncated by protease. Protease from the venom of *Echis multisquamatis* (0.01 mg/ml) was added to fibrinogen (15 mg/ml) and incubated in 0.05 M Tris-HCl buffer of pH 7.4 with 0.13 M NaCl (TBS) for 45 min at 25 °C. Fibrin polymerization was induced by 0.5 NIH/ml thrombin and prepared as described above for fibrin desAB.

Washed platelets. Venous blood of healthy volunteers (*n* = 5) who had not taken any medication for 7 days was collected by venipuncture of the basilic vein using a 19G sterile needle. Blood was collected into sterile plastic 10 ml tubes where it was mixed immediately with 38 g/l sodium citrate (9 parts blood to 1 part sodium citrate). Blood was spun down at 160 g for 30 min at 25 °C. Platelet-rich plasma was collected and spun down again at 300 g for 15 min. The pellet of platelets was re-suspended in 0.004 M HEPES, 0.137 M NaCl, 0.0027 M KCl, 0.001 M $MgCl_2$, 0.0056 mM glucose, 0.003 M NaH_2PO_4, 0.35 mg/ml bovine serum albumin (BSA), pH 7.4 to obtain a homogenous suspension of washed platelets as previously recommended [23].

Patients signed informed consent prior to blood sampling. This study was approved by the Ethics Committee of Palladin Institute of Biochemistry (03.09.2015, N7).

Human umbilical vein endothelial cells (HUVEC). Umbilical cord sampling was performed after the delivery. All birthing mothers signed informed consent prior to delivery. All manipulations were conducted under the license of the Ministry of Health of Ukraine given to the Institute of cell therapy, Kyiv, Ukraine. The umbilical vein was washed and poured with 0.1% solution of collagenase in PBS and incubated for 30 min at 37 °C. The obtained suspension was spun down and cultivated in Dulbecco's Modified Eagle's medium (DMEM) with 15% fetal bovine serum (FBS, Gibco, Dublin, Ireland) 5 mM HEPES, 2 mM L-glutamine, and 20 ng/ml fibroblast growth factor (FGF, Biochrom, Cambridge, UK) in Petri dishes. After 2 passages HUVEC were seeded on plates covered with fibrin scaffolds or untreated plates (controls). Cells were cultivated during 6 passages. To confirm that we obtained endothelial-derived cells we used flow-cytometry with specific labeled antibodies (Becton Dickinson, Franklin Lakes, USA): anti-CD34 APC, anti-CD90 FITC, anti-CD45 APC-Cy7, anti-CD105 PerCP-Cy 5.5, anti-CD73 PE, and anti-CD31 PE. Analysis was performed on the laser flow-cytometer BD FACSAria (Becton Dickinson) using the software FACSDiva 6.1.2. (Becton Dickinson) Immunophenotyping demonstrated that cells grown on all studied plates belonged to the HUVEC type having a phenotype CD31+CD105+CD73+CD90-CD34-CD45.

Mouse aortic endothelial cells (MAEC). MAEC (ThermoFisher Scientific, Waltham, USA) were grown on 96-well plates covered with fibrin scaffolds as described above, in Iscove's modified Dulbecco's medium (Sigma-Aldrich, St. Louis, USA) supplemented with 10% FBS and gentamicin (50 μg/ml). All cells were incubated at 37 °C in 5% CO_2.

Cancer cell culture. The lung cancer H1299 cell line was purchased from the American Type Culture Collection (ATCC, Manassas, VA, USA). H1299 cells were cultured in RPMI medium (Invitrogen Waltham, USA) supplemented with 10% FBS (Clontech, Kyoto, Japan) and 50 μg/ml gentamicin (Life Technologies Carlsbad, USA). Cells were incubated at 37 °C with 5% CO_2.

Chemicals and reagents. Adenosine diphosphate (ADP), dimethyl sulfoxide, MTT reagent, benzamidine, thrombin, and Superdex G-75 were purchased from Sigma-Aldrich. Collagen was purchased from RenaU (Kharkiv, Ukraine). Chromogenic substrate S2238 and C18 reversed phase HPLC columns were purchased from ThermoFisher Scientific. Anti-CD34 APC, anti-CD90 FITC, anti-CD45 APC-Cy7, anti-CD105 PerCP-Cy 5.5, anti-CD73 PE, and anti-CD31 PE were purchased from Becton Dickinson. All other reagents were of chemical grade provided by local suppliers.

SDS-PAGE. The molecular weights and purity of proteins were determined by SDS-PAGE using 10% or 12% gels according to Laemmli [24]. Hydrolysis products of fibrinogen and fibrin by fibrinogenase were also analysed by SDS-PAGE under reducing conditions.

FPLC chromatography. The mixture of fibrinogen (15 mg/ml) and protease (0.01 mg/ml) was incubated for 45 min in 0.05 M Tris-HCl buffer of pH 7.4 with 0.13 M NaCl (TBS) at room temperature. The reaction of hydrolysis was then stopped by addition of benzamidine at a final concentration 0.016 M. The mixture was gel-filtered through a Superdex G-75 column using the FPLC system ÄKTA (GE Healthcare, Pharmacia, Pittsburgh, USA). The column volume was 60 ml, with a flow rate of 2 ml/min. Fractions that contained proteins or benzamidine were detected at 280 nm using the Spectrophotometer Optizen-POP (Optizen, Daejeon, Korea).

Proteinase activity detection. Activity of proteinase in the volume eluted from the Superdex G-75 column was detected using synthetic chromogenic substrate S2238 – H-D-Phe-Pip-Arg-pNA [25]. An aliquot of each fraction (100 µl) was added to the well of a 96-well plate and mixed with 0.1 mM of S2238 in 0.05 M Tris-HCl buffer of pH 7.4 containing 0.13 M NaCl. Hydrolytic activity was continuously monitored at 405 nm [26].

HPLC chromatography. The chromatographic system Agilent 1100 (Agilent, Santa Clara, USA) was used for analysis of peptide fractions collected from the Superdex G-75 column with the C18 reversed phase HPLC column (ThermoFisher Scientific) at a pressure of 140 bar and flow rate of 1.5 ml per min. During 80 min, we used an increasing gradient of acetonitrile from 0 to 100% against buffered saline (0.15 M Tris HCl, pH 6.5, 0.13 M NaCl).

MALDI-TOF. MALDI-TOF analysis of purified peptide derived from fibrinogen was performed using a Voyager-DE (Applied Biosystems, Waltham, USA). H+-matrix ionization of polypeptides with sinapine acid (Sigma-Aldrich) was used. Results were analyzed by Data Explorer 4.0.0.0 (Applied Biosystems) [27].

Aggregometry. Platelet aggregation measurements were based on changes in the turbidity of human platelet-rich plasma [28]. Studies were performed on the Aggregometer Solar AP2110 (SOLAR, Minsk, Belorussia) according to the recommendations of the manufacturer. Washed platelets (200 µl) were added into the sample tube, mixed with 50 µl of fibrinogen (9 mg/ml) and activated by addition of 25 µl CaCl$_2$ (0.025 M) and 25 µl of platelet agonist ADP (25 µM). Aggregation was registered for 5 min at 37 °C.

Calculation of generation time. For the characterization of culture growth we calculated the time of generation according to the formula: "Generation time" = "Time of culture growth"/"duplication of cells", where "duplication of cells" = ln("number of collected cells"/"number of seeded cells")/ln2.

MTT test. Cell viability was measured by 3-(4, 5-diethylthiazoly-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay. Cells were plated in 96-well plates and were incubated with 100 µl of complete medium containing 1 mg/ml MTT (3-(4,5-dimethyl-thiazol-2-yl)-2,5-diphenyltetrazolium bromide, Sigma-Aldrich) at 37°C for 4 h followed by solubilization with dimethyl sulfoxide (Sigma-Aldrich). The absorbance at 540 nm was measured with a microplate reader [29].

Scratch wound-healing test. The scratch wound-healing assay was applied as previously described [30]. It is a widely used approach for estimating cell migration, and is especially useful for the study of migration of cancer cells [31]. Briefly, 4×10^5 cells were seeded into 24-well cell culture plates and allowed to grow to form a confluent monolayer (24 h). On the next day, the cells were serum-starved in RPMI medium containing 0.5% FBS for 24 prior to treatment. The monolayer was gently scratched with a sterile pipette tip to create a "scratch" 1 cm long. The wells were washed 2 times with 1 ml of the growth medium to remove the debris and smooth the edge of the scratch. Lyophilized fibrinogen was reconstituted in 50 mM Tris, 130 mM NaCl, pH 7.5 prior to the treatment. Fresh medium containing 50 µg/ml of control or truncated fibrinogen was added to cells and cells were incubated in fibrinogen-containing media for 2 h. After 2 h, media was replaced with RPMI + 0.5% FBS and cells were incubated for up to 24 h. The images of scratches were acquired at 0, 12 and 24 h post treatment. The wound area was measured and the number of migrated cells were counted using ImageJ software (National Institutes of Health [NIH], Bethesda, MD, USA). The number of cells that migrated into a zone of scratching was normalized to the vehicle-treated wells (no fibrinogen).

Statistical analysis. Results are presented as means ± standard deviation, calculated using Microsoft Excel (Microsoft Corp., Redmond, USA). Data were considered significant for $P < 0.05$.

Results

Preparation of fibrinogen desBβ1-42. Proteolytic enzyme from the venom of Echis multisquamatis was previously described as the fibrinogenase

targeted to N-terminal portions of Bβ-chains of human fibrinogen [32]. We incubated pure human fibrinogen (15 mg/ml) with protease (0.01 mg/ml) in TBS at room temperature and detected the compositions of polypeptide chains of fibrinogen using SDS-PAGE. After 45 min 90% of Bβ-chains were cleaved and we detected the larger part of the remnant chain in the same zone as the γ-chain of fibrinogen (Fig. 1, *A*). This composition of mixture and time of incubation was selected for preparative hydrolysis. The reaction was terminated by the addition of 0.016 M of benzamidine (an inhibitor of serine proteases) and inhibited the activity of the protease we used [33].

After incubation and addition of inhibitor, the mixture was fractionated using size-exclusion chromatography on a Superdex G-75 column. As shown in Fig. 1, *B*, we obtained a huge fraction of truncated fibrinogen (faction 5) and detected the elution of benzamidine by its absorbtion at 280 nm (fraction 6). We also used chromogenic substrate assay to detect the presence of proteinase in the fractions. The content of proteinase was too small for detection using optical density measurement but was enough for the detection of specific enzyme activity. Fractions from 60 ml to 80 ml of eluted volume contained different amounts of protease (fraction E). We collected whole eluted volume between fraction 5 and fraction 6 in an attempt to collect the fraction of peptides cleaved from fibrinogen by protease (fraction 7).

The collected fraction 7 was then further purified using HPLC-chromatography on a C-18 column. The major polypeptide peak was eluted by an increasing gradient of acetonitrile and collected for mass spectrometry (Fig. 2, *A*).

The performed MALDI-TOF analysis allowed us to detect the peak with the mass to charge ratio 4589 that corresponded to the polypeptide with molecular weight 4589 Da (Fig. 2, *B*). According to the software program "Peptide Mass Calculator" (http://www.peptidesynthetics.co.uk/tools/), the peptide with the molecular weight corresponded to the peptide "s qgvndneegffsarghrpldkkreeapslrpapppisgggyr", which was formed after cleavage of the peptide bond BβR42-A43. Thus, we confirmed that by using the limited proteolysis of fibrinogen by proteinase from the venom of *Echis multisquamatis*, we obtained the truncated form of fibrinogen – desBβ1-42 that was used in further studies.

Study of platelet aggregation. Platelet aggregation is strongly dependent on fibrinogen content and can be impossible without fibrinogen. To study the peculiarities of platelet aggregation in the presence of control fibrinogen or its truncated form desBβ1-42 we obtained the washed human platelets re-suspended in HEPES buffer. To control samples of platelet suspensions we added 1.5 mg/ml of control fibrinogen, to the studied samples an equal amount of fibrinogen desBβ1-42 was added. Platelet suspensions were incubated with fibrinogen in an aggregometer tube for 2 min and then platelets were activated by the addition of ADP or collagen as the most common agonists that act in a different manner. ADP is the agonist for P2Y1 and P2Y12 receptors that directly induce aggregation of platelets [34]. Collagen acts through the integrin receptor GPVI and induces platelet degranulation with following aggregation that occurs mainly under the granules constituent action [35].

We demonstrated that in both cases the initial rate of platelet aggregation did not differ (Fig. 3). ADP-stimulated aggregation was completely normal and achieved a maximal rate of 35% in the presence of native fibrinogen and in the presence of fibrinogen desBβ1-42. However constant mixing of sample in the tube for aggregometry led to the dissociation of platelet aggregates and disaggregation of platelets in the sample with the truncated form of fibrinogen (Fig. 3, *A*).

We observed the same trace in the case of collagen-induced platelet aggregation (Fig. 3, *B*). Here we observed not only disaggregation of platelets following maximal aggregation, but also a decreasing of the maximal aggregation rate on 10%. Thus, we can conclude that the residue Bβ1-42 of the fibrinogen molecule is not important for platelet aggregation but can increase the stiffness of the fibrin-platelet clot whether by forming additional points of contact between platelet receptors and fibrinogen or by stabilizing the structure of fibrinogen in the clot.

Study of proliferation of EC. Another important cellular component of the hemostasis involved in thrombus formation is EC. Fibrinogen is an important factor that mediates binding of other cells to EC, and also provides a scaffold for smooth muscle cells and EC during vessel tissue repair [36].

Here we studied two types of endothelial cells – primary HUVEC culture and immortalized PAE cell culture. Both types of cell were grown on the scaffolds formed with monomeric fibrin derived from control or truncated fibrinogen. For this the surface of the culturea plate with a 35 mm diameter was covered by PBS. Then an equal volume of fibrino-
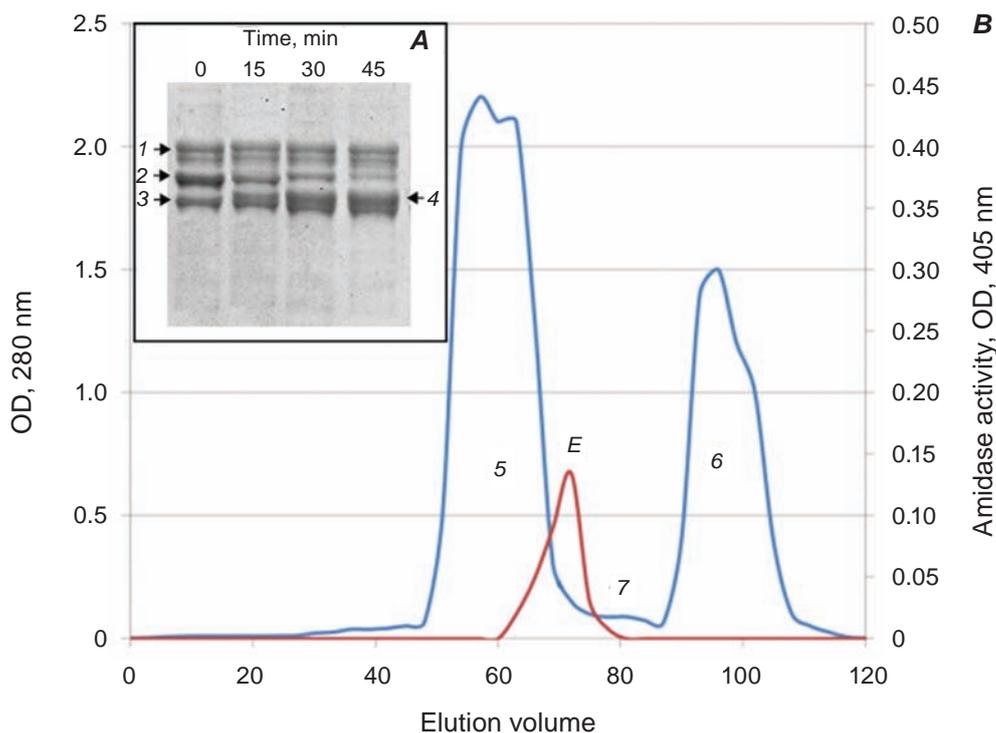
Fig. 1. Fibrinogen (15 mg/ml) digested by 0.010 mg/ml of fibrinogenase from the venom of Echis multisquamatis. A – SDS-PAGE of fibrinogen digested by fibrinogenase from the venom of Echis multisquamatis before and after 15, 30 and 45 min of digestion. 1, 2, 3 – Aα-, Bβ- and γ-chain of fibrinogen, respectively. 4 – digested Bβ-chain of fibrinogen. B – Elution of fibrinogen from Superdex G-75 column after incubation with the enzyme. Fractions: 5 – truncated fibrinogen; 6 – benzamidine; 7 – peptide zone; E – enzyme; OD – optical density

gen solution in 0.125% acetic acid was added to the plate to reach a final concentration of 0.386 mg/ml. Monomeric fibrin is insoluble at neutral pH so it was oligomerized and adhered to the surface of plate at the final concentration of 35 µg/ml.

In our studies we compared the generation time of HUVEC calculated for the different passages on the scaffolds formed with fibrin desAB (peptide composition α17-610; Bβ15-461; γ1-411), fibrin desA (α17-610; Bβ1-461; γ1-411) and fibrin desABβ15-42 (α17-610; Bβ43-461; γ1-411).

It was demonstrated that the generation time during the cultivation on fibrin desA and desAB was constant during the entire study. At the same time, cultivation on fibrin desABβ15-42 led to the prolongation of generation time that indicated slower duplication of cells and less efficient growth of the culture of HUVEC (Fig. 4, *A*). These observations were obvious in the images obtained using inverted microscopy (Fig. 4, *B*).

Another model we used for studying the effect of the fibrinogen BβN-domain on EC growth was MAEC. Cells were cultivated in a 96-well plate, and the surface of the wells were modified with fibrin as described above. The vitality of MAEC was estimated using the MTT test. The substantial decrease of viability of MAEC grown on the scaffolds formed by fibrin desABβ15-42 was observed (Fig. 5).

Thus, in two independent systems we demonstrated that the absence of the BβN-domain prominently affected the ability of fibrin to support EC proliferation. The increasing of the observed effect from passage to passage in the case of HUVEC can indicate some regulatory role of the interaction of the Bβ15-42 fragment with EC, possibly occurring through recently described interactions with VLDLR. Both HUVEC and MAEC cell lines confirmed the exceptional role of the Bβ15-42 fragment in fibrin(ogen) binding to EC.

Study of motility of cancer cells. Having sites of interactions with cancer cells on its surface, fibrinogen can stimulate cancerogenesis, as well as promote tumor growth and invasion [37]. Using our model, we estimated the role of the Bβ1-42 fragment of fibrinogen in the motility of the lung cancer cell line H1299.
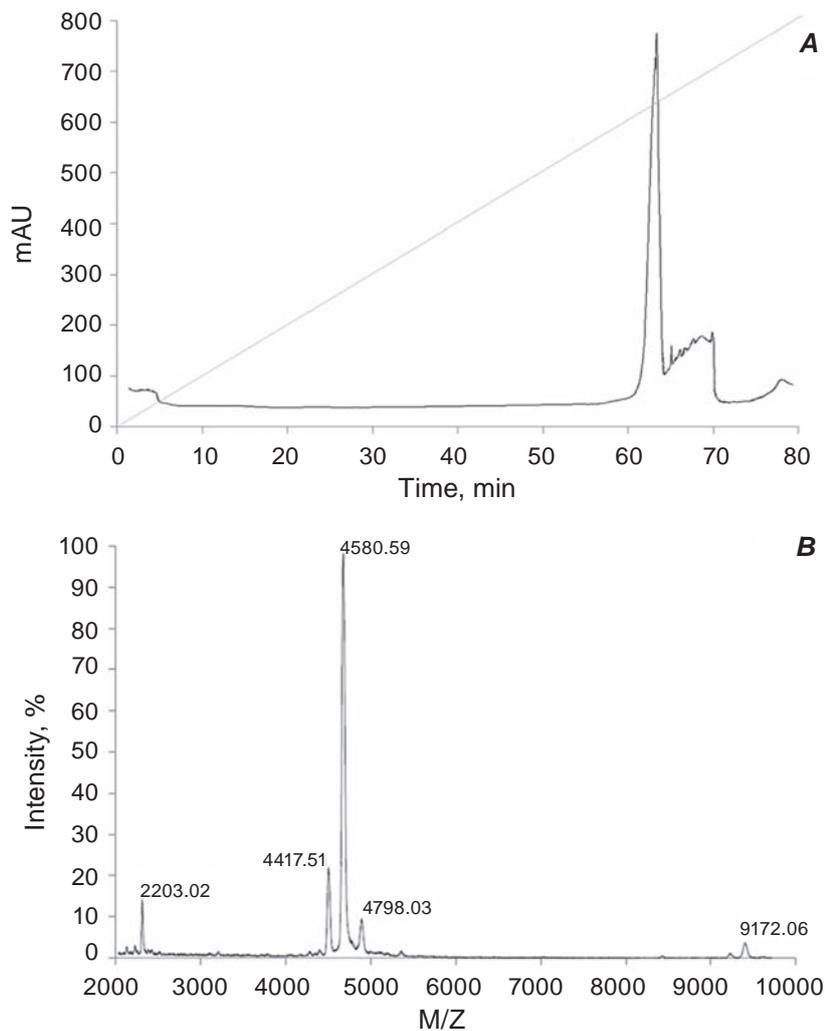
*Fig. 2. Protease-digested peptide. **A** – Purification of protease-digested peptide using HPLC-chromatography on a C-18 column. The elution was performed using a linear gradient of acetonitrile from 0 to 100% against buffered saline. **B** – MALDI-TOF spectra of peptide digested from fibrinogen by protease and purified using size-exclusion chromatography on a Superdex G-75 column followed by HPLC on phenyl-sepharose. M/Z – mass to charge ratio*

For these experiments we prepared monolayers of H1299 cells, generated scratches and observed cell migration over time in the presence of control or truncated fibrinogen (0.05 mg/ml). As shown in Fig. 9, desBβ1-42 fibrinogen modulates the motility of H1299 cells in vitro. This effect can also be observed in Fig. 6.

By this preliminary experiment we demonstrated fibrinogen lacking the Bβ1-42 region was a less effective scaffold for cancer cell proliferation. Thus, this fragment is possibly important for fibrinogen binding to cancer cell receptors. It is still unclear whether it can interact with CAM-receptors as the γ117-133 residue of fibrinogen. It would also

be important to study the direct effect of the Bβ1-42 fragment on the proliferation of cancer cells. Using the limited proteolysis technique we obtained a very useful model for testing on additional cancer cell lines. On the other hand, other receptors that can bind fibrinogen must be looked for more precisely on the surface of cancer cells, as interactions of fibrinogen with cancer cells could be a target for anticancer therapy.

Discussion

Using protease from *Echis multisquamatis* venom we obtained fibrinogen lacking the Bβ1-42 fragment and compared it to the native uncleaved
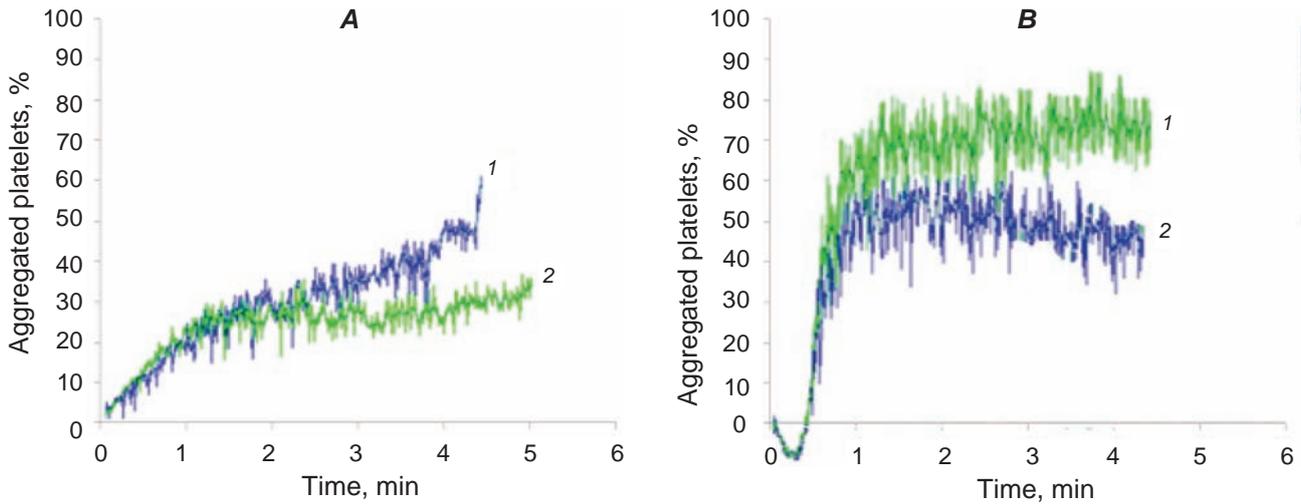
*Fig. 3. Aggregation of washed platelets activated by (**A**) 2 µM of ADP or (**B**) 2.5 mg/ml of collagen in the presence of (1) native fibrinogen or (2) fibrinogen desBβ1-42. Curves of typical experiments, n = 5*
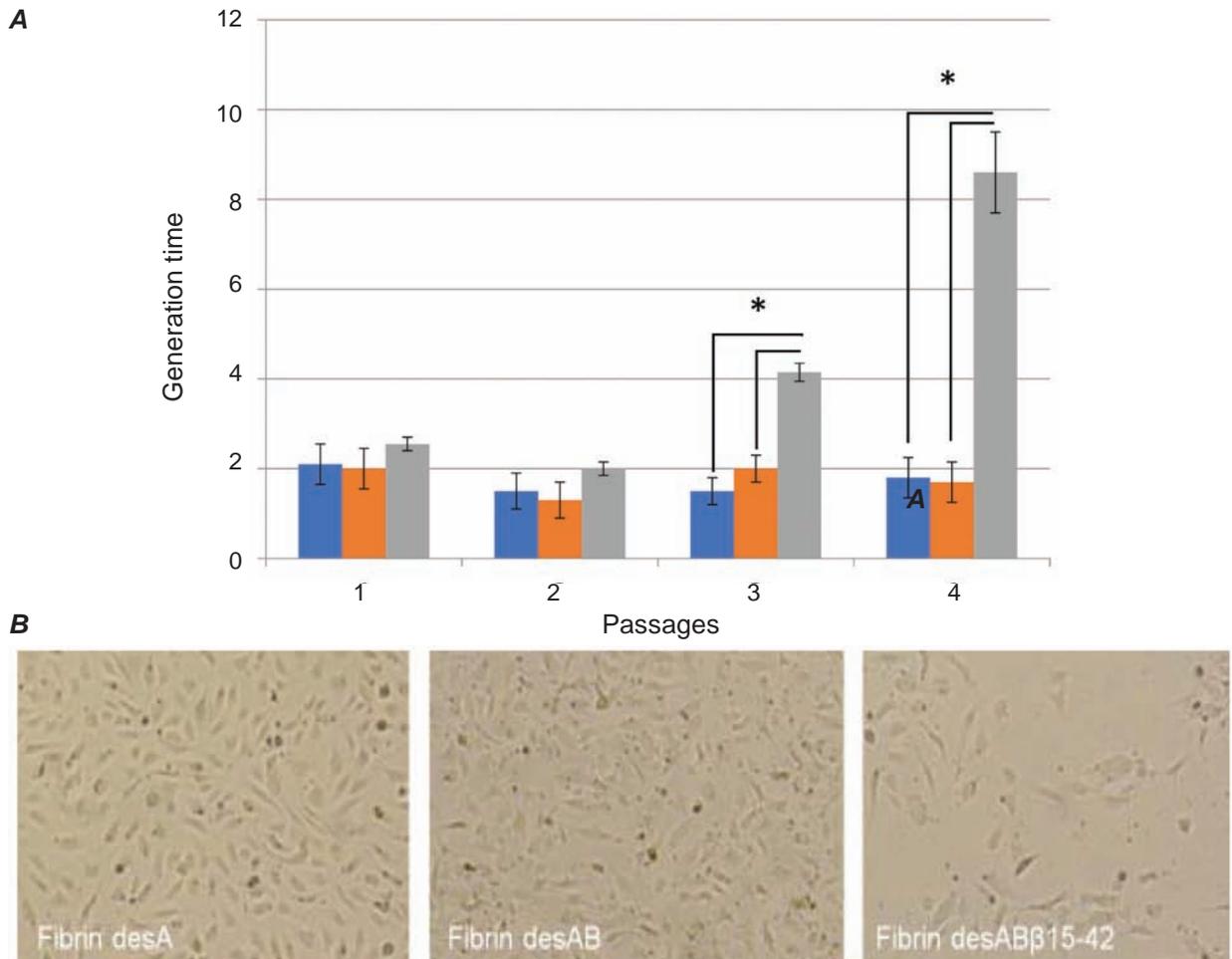

*Fig. 4. **A** – Generation time of endothelial cells cultivated on the scaffolds formed by fibrin desA (blue bars), desAB (orange bars) and desABβ15-42 (grey bars). 1-4 – number of the cell passages. Result is significant for P < 0.05. **B** – Typical view of endothelial cells cultivated on the scaffolds formed by fibrin desA, desAB and desABβ15-42 (7th passage)*
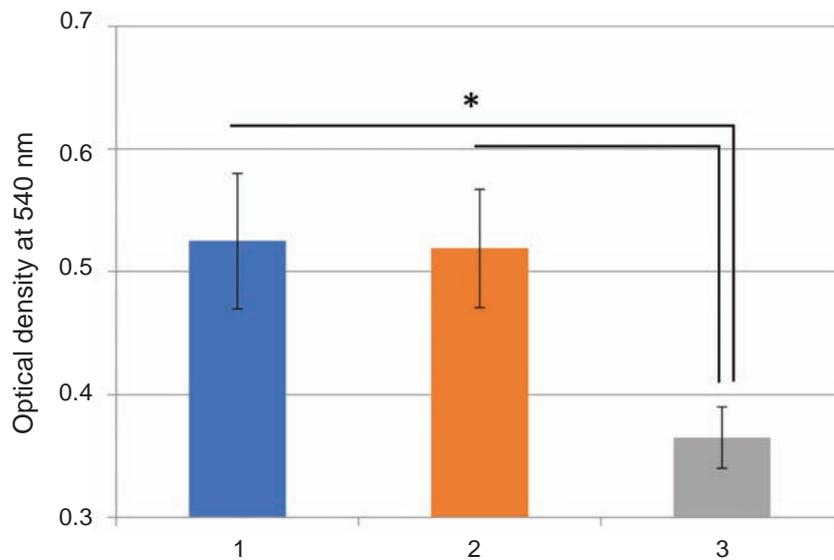
Fig. 5. Vitality of mouse aorta endothelial cells (MAEC) on the scaffolds formed by (1) fibrin desA, (2) desAB, and (3) desABβ15-42. Result is significant for P < 0.05
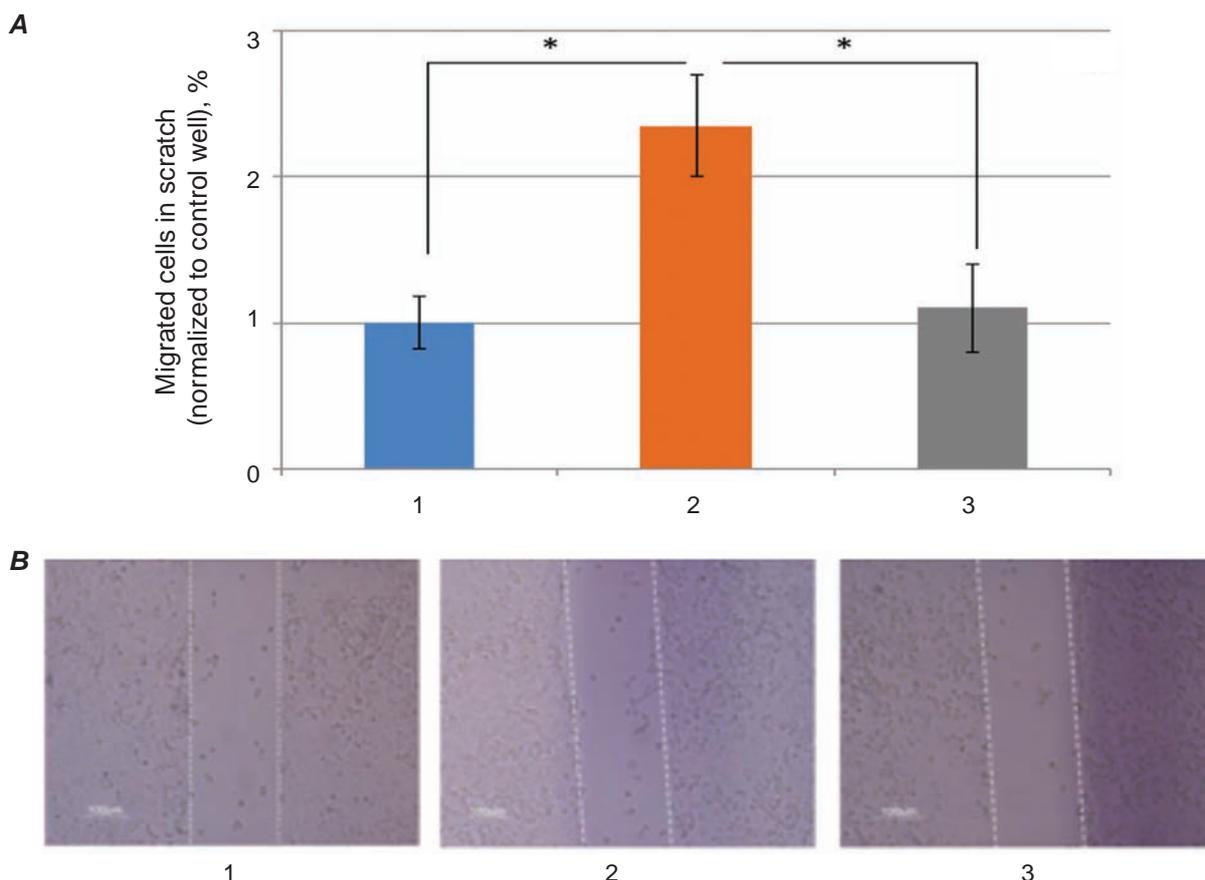

*Fig. 6. H1299 cells in vitro in the presence of (2) native and (3) desBβ1-42 fibrinogen 1 – control sample without addition of fibrinogen. **A** – Motility of H1299 cells. Result is significant for P < 0.05. **B** – Typical experiment in scratch wound-healing test: migration of H1299 cells into the scratched zone in the presence of native or desBβ1-42 fibrinogen. Zones of the original scratch are marked by white lines*

molecule in studies of aggregation of platelets, proliferation of EC and migration of cancer cells. The efficacy of all these processes were decreased in the presence of desBβ1-42 fibrinogen in comparison to the native one. The findings allowed us to conclude that the Bβ1(15)-42 fragment of fibrin(ogen) contributed to the efficient interaction with platelets, EC and cancer cells.

However, these observations were rather indirect. We studied the processes in the presence of fibrinogen without the Bβ1-42 fragment, observing the effects of cell interactions with the rest of the molecule. These results must be assessed in combination with the results that were obtained using more direct methods. To probe the role of distinct parts of the residue Bβ1-42 in physiological processes one may use recombinant technology to obtain fibrinogen with amino-acid substitutions [38, 39], and monoclonal antibodies [40, 41] or peptides [42, 43] to block some part of the residues.

Our approach based on limited proteolysis has some advantages. In particular we are working with the delicately cropped native fibrinogen molecule that has its structure, glycosylation and conformation preserved; this is impossible when using recombinant analogues. Also, monoclonal antibodies or their Fab-fragments, even polypeptides, can cause non-specific spatial obstacles for intramolecular interactions. Using truncated forms of fibrinogen allowed us to avoid these limitations.

Taken together, from our data and the data obtained by other approaches we can assume the BβN-domain of fibrinogen is an important center of fibrin(ogen) interactions with cellular receptors that can act by stabilizing the structure of the molecule (as in the case of platelet aggregation) as well as interacting directly with cellular receptors (as in the case of EC). Being also obligatory for fibrin polymerization, the BβN-domain can be a target of therapeutics that would decrease not only thrombus formation, but also decrease fibrin(ogen) adhesion to endothelium or prevent metastasis of cancer cells.

АГРЕГАЦІЯ ТРОМБОЦИТІВ, ПРОЛІФЕРАЦІЯ ЕНДОТЕЛІОЦИТІВ І МІГРАЦІЯ РАКОВИХ КЛІТИН ОПОСЕРЕДКОВАНІ Bβ1(15)-42 ФРАГМЕНТОМ ФІБРИНОГЕНУ

Є. М. Стогній[1], М. В. Рижикова[1], А. В. Ребрієв[1], М. Д. Кучма[2], Р. Ю. Марунич[1], В. О. Чернишенко[1✉], В. А. Шаблій[2], Н. М. Липова[3], О. Ю. Сломінський[1], Л. В. Гарманчук[4], Т. М. Платонова[1], С. В. Комісаренко[1]

[1]Інститут біохімії ім. О.В. Палладіна НАН України, Київ, Україна;
[2]Інститут клітинної терапії, Київ, Україна;
[3]Університет Луїсвілла, США;
[4]ННЦ "Інститут біології та медицини", Київський національний університет імені Тараса Шевченка, Україна;
✉e-mail: bio.cherv@gmail.com

Молекула фібриногену містить численні ділянки зв'язування для різних типів клітинних рецепторів і виконує роль сполучної ланки між системою зсідання крові та клітинною адгезією. У цій статті описано отримання форми фібриногену, позбавлену фрагменту Bβ1-42 за допомогою спрямованого протеолізу, для вивчення ролі цієї послідовності у адгезивних властивостях тромбоцитів, ендотеліоцитів і ракових клітин. Фібриноген та фібрин, позбавлені Bβ1-42 та Bβ15-42 фрагментів відповідно (desβ1-42 фібриноген і desABβ15-42 фібрин), отримано за допомогою протеїнази з отрути *Echis multisquamatis*. Відщеплений фрагмент отримували за допомогою HPLC та ідентифікували з використанням MALDI-TOF. ADP- і колаген-індуковану агрегацію тромбоцитів за пристуності фібриногену desBβ1-42 вивчали за допомогою агрегометра. Проліферацію клітин аорти миші (MAEC) і клітин пуповинної вени людини (HUVEC) вивчали з використанням фібрину desABβ15-42 як матриці. Виживаність клітин MAEC оцінювали з використанням MTT-тесту. Для оцінки проліферативної активності HUVEC розраховували час подвоєння.

Міграцію клітин раку легенів H1299 вивчали за допомогою *in vitro* тесту подряпини. Пряме порівняння поведінки клітин за присутності нативної та частково гідролізованої форм показало порушення процесів клітинної адгезії за пристуності фібриногену desBβ1-42 та фібрину desBβ15-42. Ступінь агрегації тромбоцитів незначно знижувався за присутності фібриногену desBβ1-42, однак було виявлено дезагрегацію тромбоцитів на рівні 15-20%. Ми також виявили значне зниження інтенсивності поділу клітин HUVEC та інгібування виживаності клітин лінії MAEC вирощених на матриці з desABβ15-42 фібрину. Крім того, фібриноген desBβ1-42 модулював рухливість клітин лінії H1299 *in vitro* і знижував інтенсивність "заростання подряпини" до 20% порівняно з повнорозмірним фібриногеном. Показано, що фрагмент 1-42 BβN-домену молекули фібриногену не є необхідним для агрегації тромбоцитів, однак вносить вклад у формування фібриново-тромбоцитарного тромбу на пізніших стадіях. У той же час, цей фрагмент може бути важливим для забезпечення міцних міжклітинних контактів та виживаності ендотеліоцитів. Також амінокислотна послідовність 1-42 BβN-домену підтримує міграцію ракових клітин, що дозволяє розглядати взаємодії з фібриногеном як потенційну мішень протиракової терапії. Фрагмент Bβ1-42 молекули фібриногену вносить вклад у ефективність міжклітинних взаємодій різних типів клітин, включаючи тромбоцити, ендотеліоцити і ракові клітини.

К л ю ч о в і   с л о в а: фібриноген, адгезія, міграція клітин, ендотелій, проліферція клітин, тромбоцити.

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