Aims
The records of early fishes in the Ordovician – Devonian are often represented by isolated body exoskeletal elements such as the scales and spines. The large number of chondrichthyan taxa occurred in this interval has been described based on isolated scales. The internal structure of scales in the recent and some fossil chondrichthyan fishes was studied based on cross sections utilized the optical microscope since 19th century (Agassiz, 1833-1843). This traditional method allows to research the details of skeletal tissues but the specimens were destroyed. The utilization of micro-CT with visualization software allows examination of the internal structure and reconstruction of the 3D model of canal system in the exoskeletal elements such as chondrichthyan teeth and scales without destroying the specimen (Abel et al., 2012). The canal (vascularization) system is poorly studied in the scales of the Palaeozoic chondrichthyans.

The scales of chondrichthyans occur growing and non-growing (Reif, 1978). The morphogenetic types of the scales are distinguished on simple monodontodia, complex monodontodia and polyodontodia depending on the structure and arrangement of odontodes (Karatajute-Talimaa, 1992). In this investigation the scale internal structure included the vascularization system was studied in the scales of different morphogenetic types and groups of the Palaeozoic chondrichthyans.

Method
The following specimens were studied utilized micro-CT: scale of Cladolepis from the Mazalovskiy Kitat Regional Stage, Givetian, Middle Devonian of Alchedat River, Kuznetsk Basin, Russia; scale of Karksilepis from the Burtnieki Regional Stage, Givetian, Middle Devonian of Karksi outcrop, Estonia; scales of orodontid and ctenacanthid types from the Steshev Regional Stage, Serpukhovian, Early Carboniferous of Zabor’e quarry, Moscow Region, Russia; euselachian scale from the Sterlitamak Regional Stage, Sakmarian, Early Permian of road cut outcrop in the Chelyabinsk Region, Russia.

The internal structure of the chondrichthyan scales was reconstructed utilising a SkyScan 1172 Bruker-microCT (Center for Geo-Environmental Research and Modeling “GEOMODEL”, Research park of St. Petersburg State University). The specimens were scanned at a voltage of 55 - 96 kV and 104 - 167 mA, with a aluminium/copper or aluminium filter for a rotation of 180° at the highest camera resolution, with an average rotation step of 0.4°. The virtual cross-section images were generated from the 3D reconstruction used to achieve 3D volume rendering with the software InstaRecon, DataView, CTAn and CTVox. The reconstruction of canal system was used the transparent mode of skeletal tissues.

Abbreviations: abc – ascending base canal, acc – ascending crown canal, b – scale base; c – scale crown; fbc – foramen of canal in the base, fcc – foramen of canal in the crown, fnc – foramen of canal in the scale neck; hbc – horizontal base canal, hcc – horizontal crown canal,
hnc – horizontal neck canal; inc – inclined neck canal; n – scale neck; od – odontode, pc – pulp canal, pca – pulp cavity.

Results
The scale of *Cladolepis* is flat, rhomboid in shape, with slightly convex base. The scale has a crown containing the odontodes placed at the different distance from each other (Fig. 1A). The odontodes are elongated, with concave middle part. The base is composed of compact lamelline tissue, missing the vascular canals (Fig. 1E). The foramina of canals are penetrated the crown surface between odontodes and around the odontode field. The network of horizontal vascular canals and their ramifications is concentrated in the crown especially in the posterior part where the odontodes are placed densely (Fig. 1B, C). The short ascending canals are connected this network with the small pulp canals of the odontodes (Fig. 1F). The scale of *Cladolepis* is growing, polyodontodia type.

The scales of *Karksilepis* possess the shape from rhomboid with convex base and long odontodes (Märss et al., 2008) to polygonal tessera-like with flat base and short odontodes (Fig. 2A, D). The scale base consists of lamellar tissue with bone cell lacunae (Marss et al., 2008). The tessera-like scale has a narrow, spiniform odontodes, inclined posteriorly and arranged at the sizeable distance from each other. The foramina of vascular canals are located at all edges of the base and on the basal side (Fig. 2D). The canal system in the scale base consists of sinuous main horizontal canals connecting by the small branches and ascending short canals penetrating the scale base (Fig. 2D, C, F). Some horizontal canals interconnect the pulp canals of odontodes (Fig. 2E). The *Karksilepis* scales are polyodontodia type with non-growing base.

The orodontid scale possesses the flat crown with compact odontocomplex, the low neck and the convex base compounded of lamelline. The central primordial odontode is surrounded the elongated additional odontodes (Fig. 3A, B). The scale neck bears the numerous foramina of neck canals opening on the lateral and posterior sides (Fig. 3D, E). The rows of foramina are located on the boundary between the odontodes (Fig. 3B). The network of vascular canals includes the meandering horizontal and ascending basal canals, as well as the branched neck canals rising to the crown (Fig. 3C, F). The orodontid scales are growing with complex polyodontodia crown.

The ctenacanthid scales possess the polyodontode complex crown, narrow neck and low, flat base (Fig. 4A-C). The odontodes are spine-like, inclined and incurred posteriorly, closely spaced and separated by narrow and deep grooves, partly fused, bearing distinct, branching carinae. The most part of odontode is composed of osteodentine. The additional odontodes diverge from the prominent primordial odontode placed in the center of the crown. The small foramina of vascular canals open in the anterior surface of the neck and base, in the basal surface of the base (Fig. 4A) but the large foramina are penetrated the posterior face of the scale neck (Fig. 4B). The very complicate network of canals is distributed within the entire scale. The ascending canals are started from the basal side of the base and continued through the neck to each odontode in the crown merged to the pulp canal (Fig. 4D-F). The ascending canals are connected each other by short horizontal or inclined branches. The inclined neck canals are formed the dense network with the ascending canals in the lower part of the crown (Fig. 4G). The ctenacanthid scales are regularly growing scales of complex polyodontodia type.
Figure 1: Scale of *Cladolepis*. A – scale in oblique crown view; B – scale in transparent mode, same view; C – virtual longitudinal section of the scale crown; D – scale in lateral view; E – virtual transversal section of the scale; F – section of the odontode group.

Figure 2: Scale of *Karksilepis*. A – scale in crown view; B – virtual longitudinal section of the scale base; C – virtual longitudinal section of the scale base, transparent mode; D – scale in oblique crown view; E – virtual transversal section of the scale; F – virtual transversal section of the scale, transparent mode.
Figure 3: Orodontid scale. A, B – scale in oblique lateral and crown views; C – virtual longitudinal section of the scale base, transparent mode; D, E – scale in posterior and lateral views; F – virtual transversal section of the scale, transparent mode.

Figure 4: Ctenacanthid scale. A, B, C – scale in anterior, posterior and crown views; D–G – virtual sections of the scale in transparent mode; D – longitudinal section of the scale; E – transversal section of the scale; F – transversal section of the crown; G – transversal section of the scale neck.
Figure 5: Euselachian scale. A, B – scale in oblique lateral and anterior views; B – virtual longitudinal section of the scale; D – scale in posterior view with virtual section of posterior parts of the crown and base; E – virtual transversal section of the scale, transparent mode; F – virtual transversal section of the crown, transparent mode.

The studied euselachian scale from the Early Permian possesses the flattened, inclined crown bearing the strong ridges, narrow neck and small flat base (Fig. 5A, B). A few foramina are penetrated the basal surface of the base, the anterior and posterior sides of the neck (Fig. 5B, D). The ascending canals run from the base to the crown where they pass into the large, pulp cavities expanded upward (Fig. 5C, F). The short horizontal neck canals are connected with the ascending ones (Fig. 5E). Such scales are probably non-growing type.

Conclusion
The studied scales of the Paleozoic chondrichthyans demonstrate the diverse internal structures: canal system and odontodes. The most complicate system of canals is observed in the growing polyodontode scales such as ctenacanthid in contrast to what was considered before. The scales with non-growing base possess the branching network of basal canals. The large pulp cavities occur only in the probably non-growing euselachian scales. The investigation of fossil scales utilizing micro-CT allows to reconstruct the morphogenesis of squamation in various groups of chondrichthyans

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