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# The Roles of K+ Currents in Human Articular Chondrocyte Electrophysiology:

# A Computational Perspective

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### Abstract:

We have developed a computational model for studying the electrophysiology of the human chondrocyte. This model is based on an initial experimental data set which identified the main K+ currents expressed in single cells isolated from knee joints of healthy adult human donors. The applicability and utility of this model are illustrated by focusing on the role of a novel 2-pore K+ current in regulating the chondrocyte resting potential and modulating intracellular Ca2+ homeostasis. This model is demonstrated to be useful for integrating available data from electrophysiological, PCR and gene array experiments. It is also an important adjunct for rationalization of working hypotheses, design of new experiments and understanding the principles and limitations of patch clamp methods as applied to the isolated human chondrocyte.

*Key words:* chondrocyte; electrophysiology; potassium currents; computational model

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**INTRODUCTION**

Articular cartilage is considered to be an aneural, avascular, alymphatic component of the flexible connective tissue that covers the articulating ends of diarthroidal joints (1-3). It is essential for the required stability and low friction movement of the associated long bones. This connective tissue consists of an extracellular matrix (ECM, composed primarily of collagen, elastin and proteoglycans, (as detailed below) and only one type of cell - the chondrocyte. Articular cartilage is exposed to cyclical mechanical forces; in fact, this dynamic environment is essential for the health of the tissue (2). Chondrocytes occupy only approximately 1-10% of the total volume of articular cartilage in mammals ([4](chondrocyte-model.html#CarneyMuir1988),[5](chondrocyte-model.html#Halletal1996)) and play no direct mechanical role. Instead, chondrocytes are responsible for synthesis and homeostasis of the extracellular matrix. Mechanical support is provided by the ECM, which is composed of (a) collagen fibers that give the tissue the ability to resist tension, (b) negatively-charged gel-like proteoglycans (PGs) that are trapped within the collagen mesh and allow the tissue to bear compression (1,8) and (c) synovial fluid within the articular capsule which acts as a lubricant, thus ensuring low friction movement of the bones (7). The primary role of the human chondrocyte is to maintain viable cartilage by balancing macromolecular synthesis and breakdown (see e.g. 2,7,9).

In a variety of conditions (including healthy aging), or as a consequence of injury, progressive chondrocyte damage and dysfunction may occur (10-12). As a result, the balance between matrix synthesis and degradation is altered and the low friction environment of the joint may be reduced or lost (9). Under these conditions, there is often an inflammatory response within the articular joint. This is one factor that increases the early development of osteoarthritis: a thinning of the cartilage layer which causes painful, bone-against-bone friction (1,11). The progression of osteoarthritis (12,13) and the ability of chondrocytes to respond to perturbations in the extracellular environment (14) are associated with deficiencies in chondrocyte volume regulation (15). It is known that physical damage to cartilage is more frequent in the setting of altered osmolarity (16). In turn, there is evidence that these volume changes are linked to an abnormal resting potential in chondrocytes (17), which may be due to changes in K+ and/or Cl- channel activity. However, direct experimental investigations that address possible functional relationships between chondrocyte electrophysiology and pathophysiology are challenging due to the small cell size of the mature chondrocyte and the associated limitations of *in vitro* electrophysiological studies. In fact, it is not at all certain that conventional patch pipette methods (18,19) can accurately determine the resting potential of isolated single chondrocytes (20). Accordingly, for the purpose of integrating available experimental data and attempting to understand its functional significance, we have developed a detailed biophysical model of human chondrocyte electrophysiology. This model can facilitate investigation of electrophysiological mechanisms, which regulate chondrocyte physiology and pathophysiology and are the targets of intra- and intercellular signaling pathways responsible for biomechanical roles, including excitation-secretion coupling.

The main goals of this work are (i) to develop the first detailed mathematical model of chondrocyte electrophysiology and (ii) to illustrate the utility of the model in investigating the dependence of the chondrocyte resting membrane potential, and by extension the volume and signaling regimes of the chondrocyte, on key voltage- and ligand-gated membrane channels.

**MODEL DEVELOPMENT AND METHODS**

The chondrocyte cell membrane is known to express a number of voltage- and ligand-gated ion channels as well as pumps and exchangers (30). Patch clamp experiments performed on enzymatically isolated individual human chondrocytes obtained with permission from a knee replacement surgery program (The Southern Alberta Transplant Service) provide the experimental basis for this model development. These chondrocytes evinced resting membrane potentials ranging from -30 to -60 mV when superfused with normal Tyrodes solution and studied using antibiotic-permeablized (amphotericin) patch clamp methods (28). This significant range of resting membrane potential values may reflect the heterogeneous physiological state of these cells. However, as we have illustrated previously, some of this variability is likely to result from the fact that in these very small, approximately spherical cells (diameter, 7 microns; capacitance 10-15 pF) the patch pipette recording method is being applied very near its technical limitations (20). That is, the input resistance of the target cell (chondrocyte) is very large (1-10 gigohms), and the seal resistance between the surface membrane of the chondrocytes and the polished surface of the glass pipette has a typical value of 1-5 gigohms. Thus, the actual chondrocyte membrane potential may be underestimated due to the current flow through the seal resistance, which in most circumstances results in an apparent depolarization. The Appendix of this manuscript describes the known biophysical principles which, when combined, regulate the ways in which the combination of patch pipette seal resistance and intrinsic input resistance result in apparent values for the resting potential in small cells such as the human chondrocyte.

The main objective of this first model is to obtain insights into the ionic mechanisms that underlie the resting potential in the human chondrocyte *in situ*. The raw data that forms the basis of this model is derived mainly from our previously published recordings of the K+ currents in human (28), mouse (31) and canine chondrocytes (32). Other elements summarized diagrammatically in Figure 1 below are obtained from published literature on isolated chondrocytes from rabbit, canine and equine tissue.

[Figure 1 near here]

## The Atypical Environment of the Chondrocyte

The chondrocyte is situated in a physiological environment that differs significantly from that of most other mammalian cells (as summarized in Table 1). Despite this unique extracellular environs, the large electrochemical gradients for Na+, K+ and Cl- across the cell membraneare very similar to those in other mammalian tissue types. These gradients lead to the requirement for an ATP-dependent Na+/K+ pump mechanism, assumed to be electrogenic, in order to maintain ionic homeostasis. Note, however, that the extracellular fluid within the articular joint is hypertonic (approximately 320 mOsm vs. blood plasma which is approximately 280 mOsm). In addition, the extracellular pH of the synovial fluid that bathes the chondrocyte is somewhat acidic, pH 7.2 (8,24) although apparently an intra- to extracellular pH gradient also typical for other cell types can be identified (references?).

The substantial number of fixed negative charges on proteoglycans immediately adjacent to the chondrocyte can attract free cations (e.g. Na+) and exclude free anions from the matrix. As a result of this cation accumulation (Table 1), there is an osmotically driven water influx to the cell. (10,17).

The articular joint receives little or no vascular supply. As a result, the synovial fluid must supply adult articular cartilage with the required small amounts of nutrients as well as oxygen to e.g., maintain Na+/K+ pump activity (33). Metabolic byproducts are removed mainly by diffusion (34,35). A second consequence of the avascular nature of this tissue is that chondrocytes generate ATP by substrate-level phosphorylation during anaerobic respiration. This generates H+ ions as a byproduct, which further lowers the pH in this micro environment. The dynamic changes in mechanical loading within the knee joint during activity also exposes chondrocytes to very significant fluctuations in vector forces and shear. The resulting mechanical changes would be expected to activate mechano- or shear-sensitive ion channels (36-40).

Experimentally-reported values for the external cation concentrations differ markedly from those of extracellular fluid in other mammalian tissues. We have also incorporated these atypical values for extracellular ion concentrations (Table 1).

**Table 1:** Consensus Values of Ion Concentrations for Chondrocyte Electrophysiology, given in millimolars (mM) ([8](chondrocyte-model.html#Wilkinsetal2000)).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| |  |  |  |  |  | | --- | --- | --- | --- | --- | |  | Cytoplasm | Matrix | Serum/Synovium |  | | [Na+]o (mM) | 40 | 240-350 | 140 |  | | [K+]o (mM) | 120-140 | 7-12 | 5 |  | | [Ca2+]o (mM) | 8.e-5 | 6-15 | 1.5 |  | | [Cl-]o (mM) | 60-90 | 60-100 | 140 |  | | [HCO3-]o (mM) | 20 | 15 | 23 |  | | [SO42-]o (mM) | 0.17 | 0.30 | 0.81 |  | | pH (mM) | 7.1 | 6.6-6.9 | 7.4 |  | | Osmolarity (mOsm) | -- | 350-450 | 300 |  | |

**Membrane Currents**

### *Background Currents*

Background or leakage conductances, including resting Na+, K+, and Cl- fluxes, are included in the present model.

The model accounts for leakage of Na+ and K+ through time-independent, non-specific cation channels using standard Hodgkin-Huxley formalism:

|  |  |
| --- | --- |
|  | (1)  (2) |
|  |  |

Where XX is XX...

And the Nernst potentials for Na+ and K+ are computed based on their respective intra- and extracellular concentrations:

|  |  |
| --- | --- |
| Where XX is XX... | (3)  (4) |

In a variety of mammalian chondrocyte preparations, one or more types of Cl- conductance have been identified (59,c.f. 30). This quasi-linear Cl- conductance has also been identified in human chondrocyte cell lines (61), and in experiments in which selected transmitters or pharmacological agonists (e.g., histamine) have been applied (62). We have incorporated this type of current into our model by treating it as a background current, specified by the equations below.

|  |  |
| --- | --- |
|  | (5) |

Where XX is XX...

and

|  |  |
| --- | --- |
|  | (6) |

is the Nernst potential due to the difference in Cl- concentration inside and outside the cell. Where XX is XX...

The current-voltage (IV) relationships for these sodium, potassium, and chloride background currents (INab, IKb, and IClb, respectively) are shown in Figure 2A.

### *Ion Pumps and Exchangers*

**(a) Na+/K+ Pump**

The active extrusion of Na+ ions from the chondrocyte is assumed to be achieved by the turnover of an electrogenic Na+/K+-ATPase. Mobasheri et al (33) have characterized some of the functional properties of an electrogenic Na+/K+ pump in bovine articular chondrocytes. Cell volume is maintained by altered balance of leaks and pumps to hold cell water constant. In this model, we employ the following sodium-potassium pump formulation (42):

|  |  |
| --- | --- |
|  | (7) |

Where XX is XX...

This conductance has been scaled to achieve a steady-state intracellular Na+ concentration of 10-12 mM.

**(b) Na+ /Ca2+ Exchanger**

As in many other cell types, the Na+/Ca2+ exchanger plays a key role in Ca2+ homeostasis in articular chondrocytes (41). We model this electrogenic exchange process using the following mathematical expression (42).

|  |  |
| --- | --- |
|  | (8) |

Where XX is XX...

This conductance has been scaled to achieve an intracellular Na+ concentration of 12 mM, and assumed free intracellular Ca2+ concentration of 3 x 10-8 M.

**(c) Na+ /H+ Exchanger**

Chondrocytes express a Na+/H+ antiporter (43,44), which allows the cell to regulate pH and establish an intra- to extracellular pH gradient. This pH gradient is essential for maintaining intracellular Na+ levels and the intracellular pH indirectly regulates a number of essential enzymatic processes in both physiological and pathophysiological settings.

In order to model this channel, we use the following functional form (45):

|  |  |
| --- | --- |
|  | (9) |

where,

|  |  |
| --- | --- |
|  |  |

### Figure 2B shows I-V curve for these electrogenic pump and exchangers INaK, INaCa, and INaH.

1. Where XX is XX...

### *Potassium Currents*

This model also incorporates mathematical expressions for a total of four distinct K+ currents identified from electrophysiological studies performed on mammalian chondrocytes. Two of these, a delayed rectifier K+ current, which we denote IK-DR, and a K+ current due to a 2-pore K+ channel, which we denote IK-2P, have been studied in detail in our laboratory (28,32) and by others (45-57). The remaining two K+ currents, a Ca2+-activated K+ current (IK-Ca) and an ATP-dependent K+ current (IK-ATP) have been identified in other patch clamp studies. These are also included.

**(a) Delayed Rectifier K+ Current: IK-DR**

A time- and voltage-sensitive K+ current has been identified in the human articular chondrocyte (28-32). The biophysical properties of this current and the details of its pharmacological blockade suggest that it is generated by the family of alpha subunit K+ conductances denoted Kv1.4 or Kv1.6. Accordingly, IK-DR is modeled by the following:

I\_K-DR = g\_K\_dr\*a\_dr\*(V - E\_K) (10)

where a\_dr is computed as part of the system using:

a\_dr\_inf   = 1.0/(1.0 + exp(-(V + 26.7)/4.1))

tau\_a\_dr   = 0.005/(1.0 + exp((V + 5.0)/12.0))

in our model.

Where XX is XX...

Panel A of Figure 3 shows an experimental I-V relationship generated under physiological conditions, that is, a normal electrochemical gradient for K+, with the corresponding model results. Figure 3B shows steady-state activation, and Figure 3C illustrates the kinetics of activation and inactivation.

[Figure 3 near here]

**(b) 2-Pore K+ Current: I­K2pore**

Our recent work has identified recording conditions under which an additional K+ current, generated by what is believed to be the TASK family of 2-pore K+ channels (28), is measured (I­K2pore­­). These channels show no detectable time dependence; TASK channels additionally show a significant increase in conductance in response to an increase in pH or alkalinization of the extracellular medium. A peak I-V curve for this current is shown in Panel A of Figure 4, while Figure 4B illustrates the enhancement of this current when extracellular pH was changed from XX.

These recordings were performed under conditions of elevated extracellular K+ so channel currents were of a detectable magnitude such that biophysical properties could be resolved. Before this data could be appropriately represented and incorporated into the mathematical model, it needed to be corrected to physiological conditions. This was achieved via the Eisenman principle (54): the conductance of an ion-selective channel scales according to the square root of the extracellular concentration of that permeant ion. The I-V curve in Figure 4C shows the original data recorded in isotonic K+ (~145 mM), with the expected reversal potential of 0 mV, together with the corrected data (assuming external K+ to be 5.4 mM with a corresponding reversal potential of approximately -85 mV).

[Figure 4 near here]

Using the classic Goldman-Hodgkin-Katz equation (54) for voltage-gated, time-independent single-species ion channels, this current can be represented by:

|  |  |
| --- | --- |
|  | (11) |
| Where XX is XX... |  |

Figure 5 shows the current-voltage curve as fitted to experimental data (28) obtained in isotonic conditions (panel A), and when corrected for an assumed normal extracellular potassium concentration of 5.4 mM (panel B). Experimental work also demonstrated that this particular K+ current was strongly inhibited by bupivacaine; an effective concentration of bupivacaine also resulted in a significant depolarization of the resting potential (see Discussion).

[Figure 5 near here]

**(c) Ca2+-Activated K+Current: IK,Ca-act**

Virtually all recordings of global K+ currents in human chondrocytes include a significant and very noisy outward current at depolarized potentials (55,56). The spontaneous fluctuations of this current suggest that it is generated by the so-called large conductance (often called BK) variant of the Ca2+ activated K+ current family (57). We have not explored the biophysical properties of this current or its pharmacological profile in any detail. However, it is consistently present in our recordings and a Ca2+-activated K+ current (IK,Ca-act) has also been described in isolated chondrocytes from rabbits, dogs and horses (47), and is thus included in the present model.

For the given data set (34), the (large) Ca2+-activated K+ channel can be represented by (57,58):

|  |  |
| --- | --- |
|  | (12) |

where,

|  |  |
| --- | --- |
|  |  |

Where XX is XX...

Figure 6 shows the current-voltage relationship for this current as fit to recent experimental data.

[Figure 6 near here]

**d) ATP-sensitive K+ Current: IK,ATP**

An ATP-sensitive K+ current has been reported in chondrocytes from a variety of mammalian species (59). Previous experimental work in human articular chondrocytes (34) did not address this possibility and there are no reports of this current being activated in human chondrocytes in the literature. However, the hypoxic environment of the articular chondrocyte makes the presence and the activation of this current during normal biomechanical activity plausible, and thus this current (IK,ATP) is included in the present model, as shown in Figure 7:

IK,ATP = sigma\*g\_0\*p\_0\*f\_ATP\*(V - E\_K) (15)

Where XX is XX...

[Figure 7 near here]

***Other Sarcolemmal Currents***

**Transient Receptor Potential or TRP Current: ITRPV4**

Ligand-gated channels that exhibit properties similar to TRP ion channels are expressed in mammalian chondrocytes (63), and the TRPV4 family is prominently expressed in mouse chondrocytes (64,65). It is likely that this type of conductance is needed to explain chondrocyte electrophysiological responses to naturally occurring paracrine substances (e.g., ATP) or to cytokines that are liberated in the setting of acute or chronic inflammation (e.g., XX). A further reason for incorporating this type of conductance into this early model is that this type of ion channel exhibits significant permeability to both Na+ and Ca2+ (68). Either or both of these cation species are likely important in regulating excitation-secretion coupling and could modulate cell volume. It is also known that this type of ion channel can couple to purinergic receptors and/or to specific connexin proteins which function in the context of intercellular electrotonic communication, or as hemi-channels. On these bases, the TRPV4 ligand-gated ion channel, thought to be involved in the regulation of systemic osmotic pressure, has been incorporated into this initial model of the human chondrocyte as ITRPV4 (see Figure 8).

[Figure 8 near here]

|  |  |
| --- | --- |
|  | (13) |
|  |  |

Where XX is XX...

***Intracellular Ca2+ Homeostasis***

The chondrocyte’s intracellular Ca2+, [Ca2+]i, is maintained by the sodium calcium exchanger (eq. 8), a sarcolemmal electroneutral Ca2+ ATP-ase (eq. 12) and via intracellular buffering (eq. 13 and 14). In the absence of more concrete data, the intracellular Ca2+ buffering in the present model is attributed mainly to calmodulin within the cytosol and is represented as in our previous models of the atrial myocyte (42,48).

I\_Ca\_ATP = I\_Ca\_ATP\_bar\*(Ca\_i/(Ca\_i + k\_Ca\_ATP)) (12)

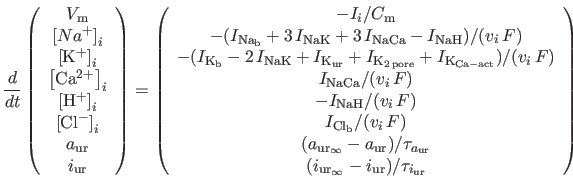
dO\_c/dt = 200,000\*Ca\_i\*(1.0 – O\_c) - 476.0\*O\_c (13)

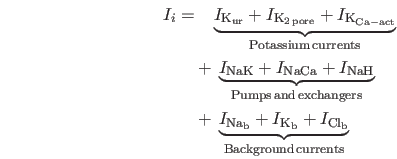
dCa\_i/dt = (I\_NaCa - I\_Ca\_ATP)/(vol\_i\*F) - 0.045\* dO\_c/dt (14)

Where XX is XX...

## Model Implementation

In this first-order model, spatial variations in quantities of interest are not accounted for. As a result, the human articular chondrocyte can be modeled by the following set of ordinary differential equations (ODEs) in time:

 (15)



Where XX is XX...

The system of ordinary differential equations defined above was solved using LSODE (68). All initial conditions were chosen from previous calculations run to steady state. The corresponding GNU Octave code is available freely and is open source.

**RESULTS**

***Whole-cell current-voltage relationship***

After primary parameteristion, the overall model behaviour was studied under a linear voltage ramp from -130 mV to +90 mV under conditions matching experiments ([K+]o = 5 mM, [Na+]o = 140 mM, [Ca2+]o = 2 mM, pH = 7.4) to reveal that the overall voltage-current behaviour of the chondrocyte model reproduces the experimental whole-cell current-voltage data quite closely (28). This comparison is shown in Figure 9 below; note the resting membrane potential of approximately -60mV.

***Ligand-gated ion channels and chondrocyte resting membrane potential***

Simulation of the electrophysiological response following activation of ITRPV4 is shown in Figure 10A. The effect of this channel-mediated current on the human articular chondrocyte resting membrane potential can be deduced by adding this current to the steady-state I-V relation (blue trace); it is clear that activation of TRP channels results in a transient depolarization of the chondrocyte (green trace) of approximately +20mV. The effects of a mechanical-impulse-related increase in TRPV4 conductance is additionally shown in Figure 10B; it is apparently that the resting membrane potential of the chondrocyte is further depolarized by approximately +10mV.

[Figure 10 near here]

**DISCUSSION**

***Resting Membrane Potential in the Human Chondrocyte***

In the present state of development, the model represents an original but semi-quantitative tool to be used in continued multidisciplinary studies of electrophysiological and biophysical principles of the human articular chondrocyte. Our initial emphasis was on investigating the basis of the resting potential (Vrest), since our data set consists mainly of K+ current measurements in this non-excitable cell. Moreover, it is known that even very small changes in the resting membrane potential can strongly modulate factors that govern intracellular Ca2+ signaling and homeostatic mechanisms. There is also evidence that relatively small alterations in membrane potential contribute to dynamic regulation of cell volume (ref). In addition, both the strength and duration of ligand-gated conductance changes are dependent upon membrane potential (Vrest) since this sets the electrochemical driving force.

The computations shown in Figures 2 through 9 do not fully explain the ionic basis for Vrest in the human chondrocyte. Rather, they serve to illustrate that a range of membrane potential values are to be expected in this cell type, as the net outward current that sets the resting membrane potential at steady-state is quite small (the algebraic sum of background conductances as well as currents due to the electrogenic Na+/K+ pump and Na+/Ca2+ exchanger). In many recording situations the leak current through the patch pipette seal resistance can influence (and could even dominate) the observed ‘Vrest' (see Appendix). In addition, spontaneous changes in this seal resistance can give the impression of an unstable resting potential in these cells.

Nevertheless, this work provides a basis for determining the physiological roles of each of the four K+ currents identified and characterized in human chondrocytes. It is evident from the computed I-V curves (Figure 3, 5, and 6) that any, or all of these currents could: i) significantly hyperpolarize the resting potential or ii) repolarize the chondrocyte after it had been depolarized by e.g., the effects of mechanical activity or by via a ligand-gated conductance.

It is interesting to note that TRPV4 channel activation (as explored in Figure 10) would result in a significant influx of Ca2+ and Na+ when the chondrocyte membrane potential is negative to approximately -40 mV. TRP channel-induced depolarization would be transient, and likely limited in magnitude, eventually transformed into a repolarization by the voltage-dependent activation of the delayed rectifier K+ current, IK-DR. It follows that when activation of TRP channels results in a significant increase in intracellular Ca2+, the Ca2+-dependent K+ current, IK,Ca-act, will also be activated. These potassium currents hyperpolarize the chondrocyte membrane potential and this potential will be maintained until intracellular Ca2+ and/or Ca2+-dependent signaling mechanisms reset to “resting” values.

The physiologic milieu within the articular joint presents conditions under which some of these K+ currents may be modulated significantly. For example, the extracellular fluid is hypertonic. The effects of osmolarity on voltage gated K+ currents have been studied extensively. In brief, as a consequence of changes in surface charge, shielding alterations in superfusate tonicity can significantly shift the steady state gating of currents such as IK-DR. Experimental work (28) was performed under fixed isotonic conditions. The literature would suggest that an increase in osmotic strength would cause a shift in steady state gating to the right, in the depolarizing direction, by perhaps 5 mV. This biophysical correction suggests that IK-DR does not make any significant contribution to the resting potential. However, this alteration would position this current to initiate prompt repolarization following any transient depolarization (e.g. via TRPV4 activation), while also ensuring that the input resistance of the cell at the resting potential remained very high. This is a critical factor, since a minimum of ion transfer may be desirable in the relatively hypoxic milieu of the articular joint.

***Practical Applications of the Model***

**Injury and Healing in Athletes**

Early signs of osteoarthritis may develop even in young individuals following articular joint injury. This is thought to be due to a phenomenon denoted 'chondrolysis', a condition in which accelerated loss of articular cartilage occurs over a short time period (21-23). Several clinical studies have also documented that this significant pathophysiological response can occur as a result of postoperative administration of bupivacaine, a local anesthetic. Experimental work has confirmed that bupivacaine can cause profound effects including chondrocyte death in both isolated cell experiments (24) and associated animal studies (25-28). However, the cellular and subcellular mechanisms responsible for this toxic response (characterized by increased apoptosis) are not completely understood. In this regard, it is interesting to note that a family of two-pore K+ channels that have been recently identified in human articular chondrocytes can be inhibited by bupivacaine (29). Bupivacaine-induced block of these and other (29) 2-pore K+ channels can result in a pronounced depolarization of the chondrocyte (ref). It is thus important to gain a detailed understanding of resting membrane potential, intracellular Ca2+ levels (that can regulate apoptosis) and cell volume which can modulate excitation-secretion coupling. Future work employing the present model and its descendants will shed light on the functional relationships between these actors.

**Connexin-Mediated Current Flow**

The chondrocyte from adult humans functions as an isolated cell. As a result, it may seem that consideration of connexin function is irrelevant. However, data from humans during early adolescence suggest that the growth plate of articular joints is characterized by small groups of directly opposed chondrocytes with expression of selected members of the connexin family being detectable using standard immunohistochemical approaches (66). Moreover, it is now known that even in the case of isolated adult cells, prominent ATP release can be observed (67). One plausible mechanism for this chemical or mechanical release is transient opening of HEMI channels due to expression of either pannexin or connexin subunits. For these reasons, our model incorporates a connexin-mediated conductance which, under physiological conditions is shut off (has a conductance value of 0 pS). However, the present model would be facile tool for future exploration of connexin-mediated current flow and its implications, as well as exploration of multi-cellular chondrocyte substrates as occurring in the human articular growth plate.

***Limitations and Model Summary***

We recognize that, at this stage, our model has significant limitations. These include but are not limited to:

a) Mathematical expressions that would allow rationalization of what has been termed 'the AM and FM modes of Ca2+ signaling', which will require consideration of intracellular Ca2+-dependent phosphorylation and dephosphorylation reactions and consideration of the Ca2+-dependence involved in transcriptional regulation of ion channel, antiporter and pump target molecules.

b) An improved understanding of and development of mathematical approaches that may account for the response of the chondrocyte to the ambient hypoxia within the articular joint. Initially this is likely to require formulation of equations for hypoxia-activated K+ channels.

c) Adaptation of published mathematical formulations for alteration of ion channel activity arising from cyclic biomechanical stretch or from transient changes in shear forces that impinge upon the chondrocyte.

As presented, this mathematical model of chondrocyte electrophysiology provides a reliable platform for explaining and evaluating recent experimental data. This first-order model also has proven utility for rationalizing and integrating genomic data from expression array profiles and as part of ion channel/antiporter drug target initiatives. Iterations based on the semiquantitative approach made possible by this model can also be useful for designing new experiments that are aimed at revealing cellular mechanisms that govern and modulate excitation-secretion coupling, as suggested in the previous section. Finally, given that the chondrocyte is in a unique, but yet not completely defined microenvironment our model provides a basis for explaining: i) the known biophysical effects of alterations in ionic strength of synovial fluid on ion channel voltage-dependent gating (zeta potential effects), ii) one common approach in attempts to account for the effects of cyclic stretch on ion channels - strain dependent alterations in channel gating voltage dependence or kinetics (cf. XX), and iii) much needed approaches for detecting and determining the limitations of present patch clamp technology that can bias, if not dictate, resulting data sets and influence their interpretation.

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CONFLICT OF INTEREST:

None of the authors have any conflict of interest items to declare.

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### Figure 1. An illustration of the ion-selective channels included in the mathematical model of the chondrocyte.

### Figure 2. Background & pump currents

### A. Background currents Na+, Ca2+, K+

### B. pump/exchanger currents

### C. Net current, A+B, measured slope resistance in range of 1-2 Gohms

### Figure 3. I\_K-DR

### A. IV curve, peak

### B. Activation curve

### C. Kinetics

### Figure 4. I\_K2pore (A, B, C, all experimental)

### A. peak IV

### B. peak IV with increased pH

### C. isotonic measurement data and "corrected" data

### 

### Figure 5. I\_K2pore in computation and corrected experiment

### Figure 6. Ca2+ -activated K+ current, experimental and computed

### Figure 7. ATP-sensitive K+ current, computed only

### Figure 8. TRP4V channel, computed only

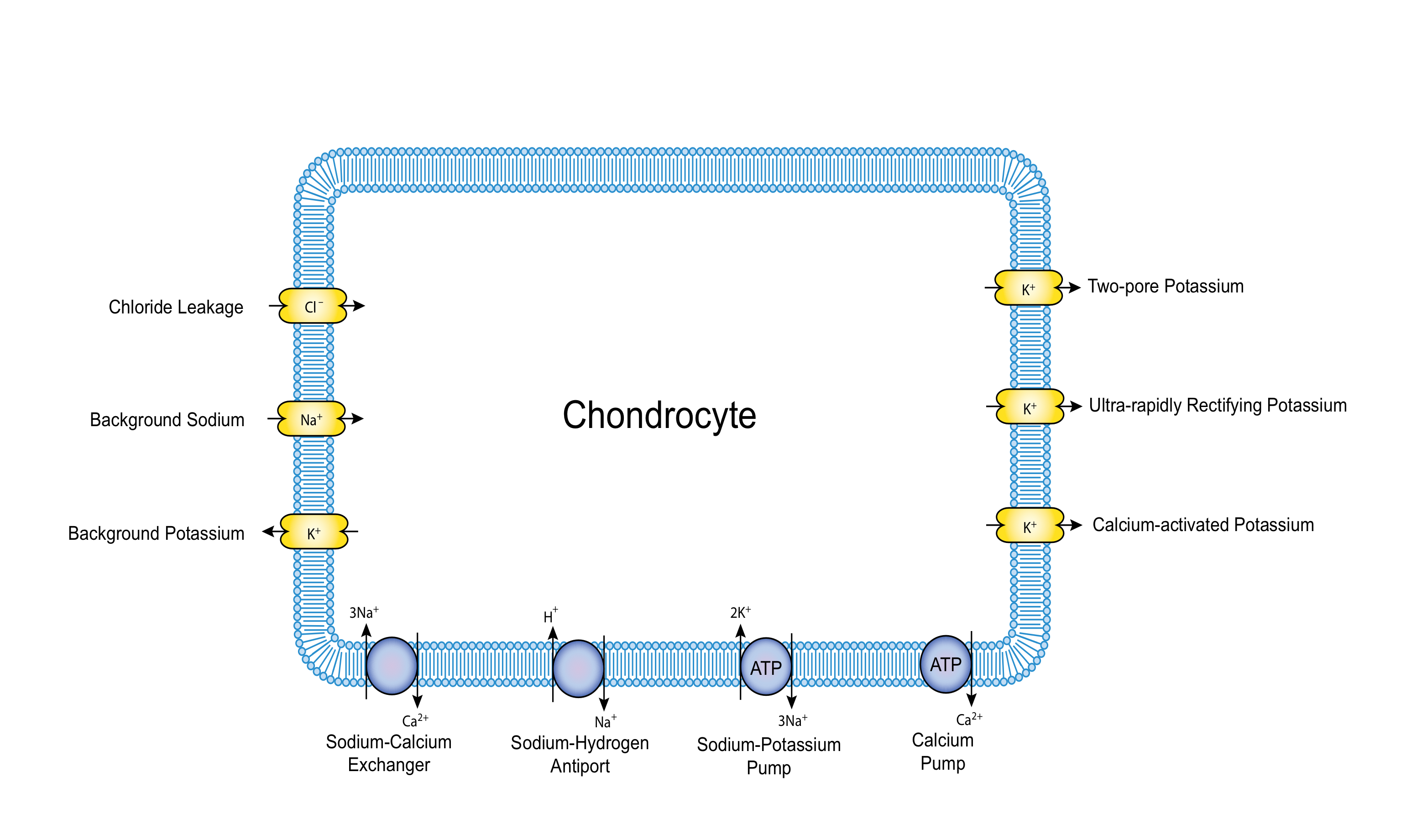
**Figure 9.** Whole-cell current-voltage relationship as compared to model results.

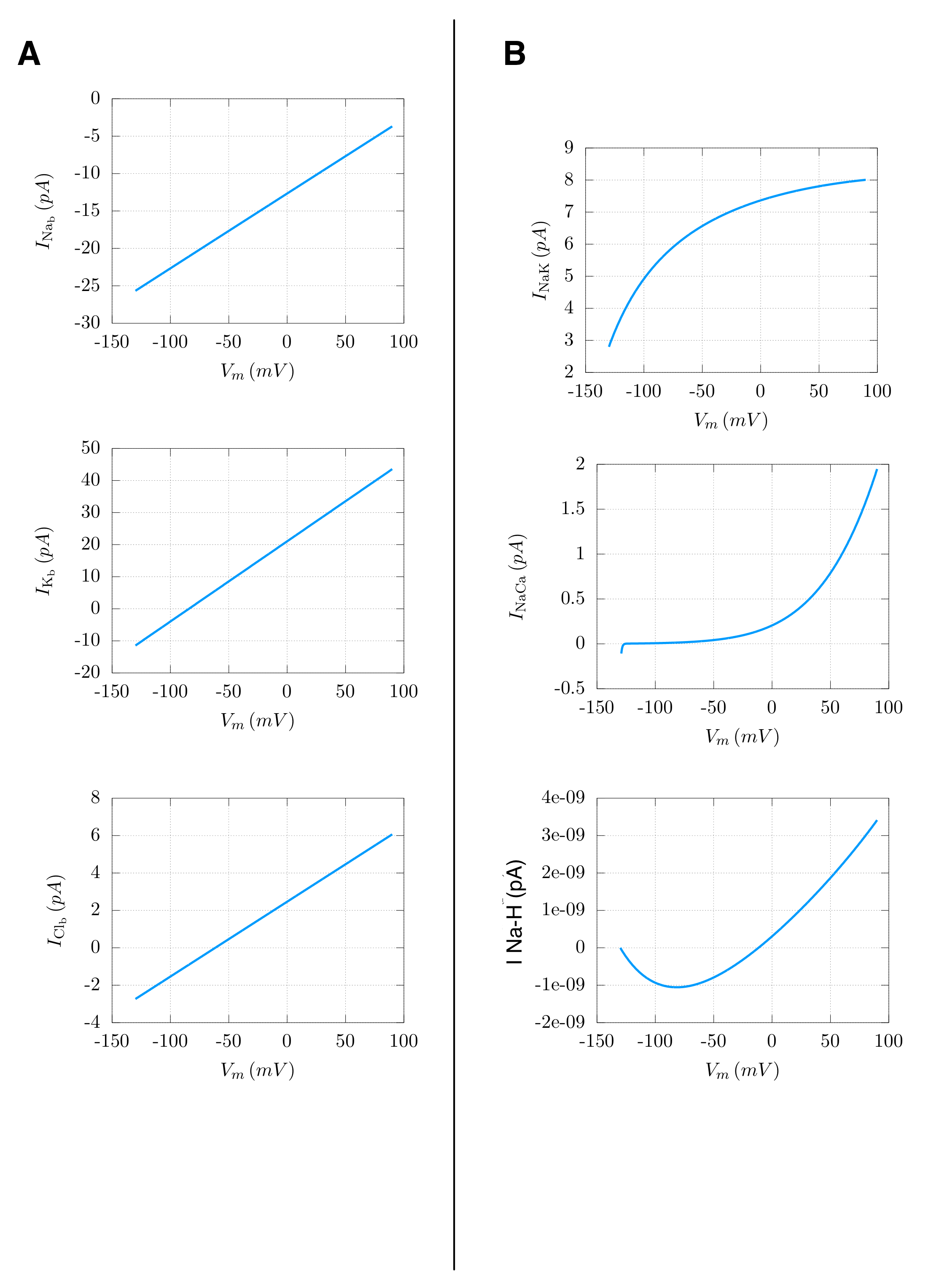
**Figure 10.** In Discussion; activation of TRPV4 influence on RMP

A. Cell IV-relation including computational TRPV4 and without + experimental

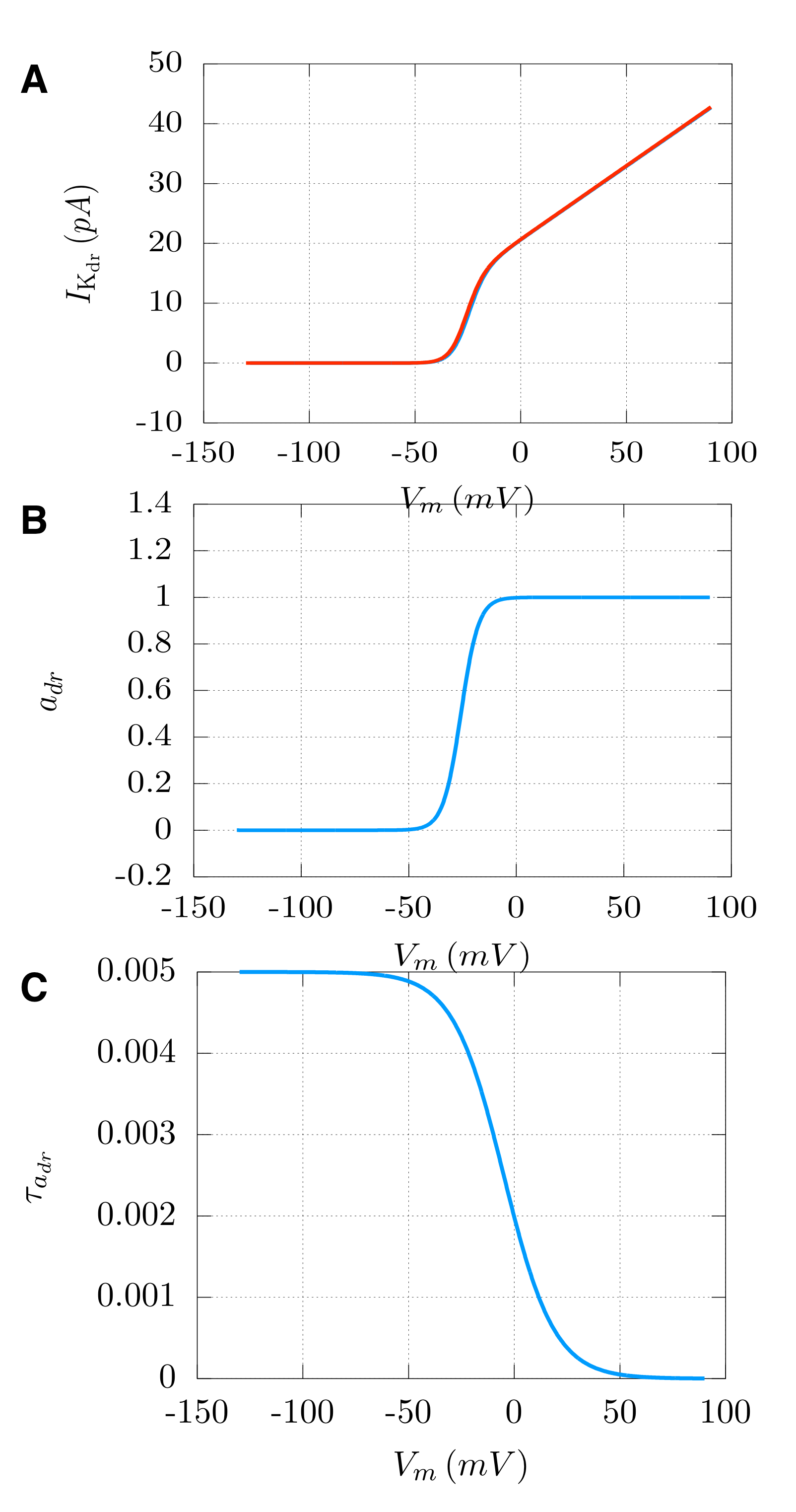
B. Stretch increases the conductance 3-fold

**Figure 1**

**Figure 2**

****

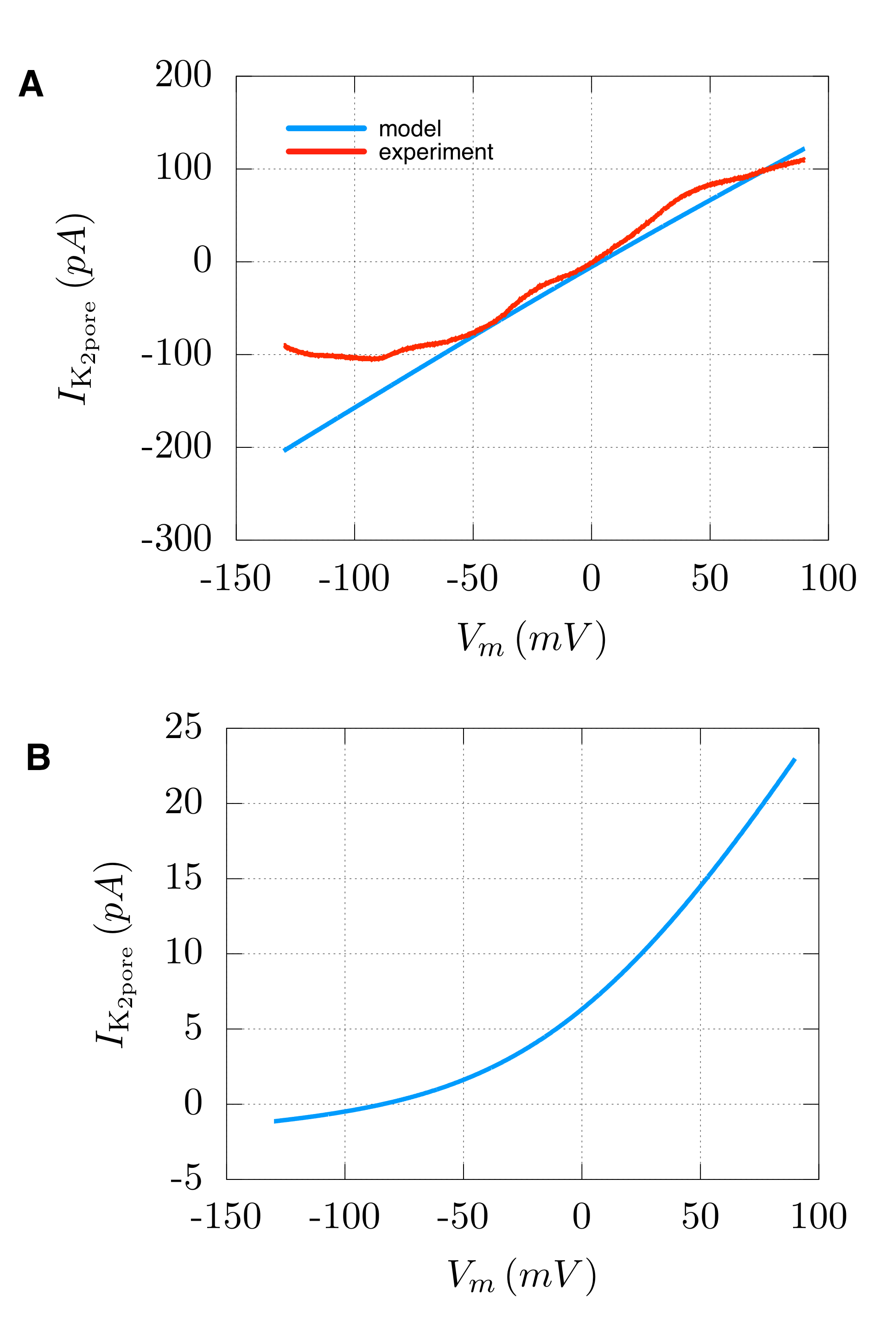
**Figure 3**

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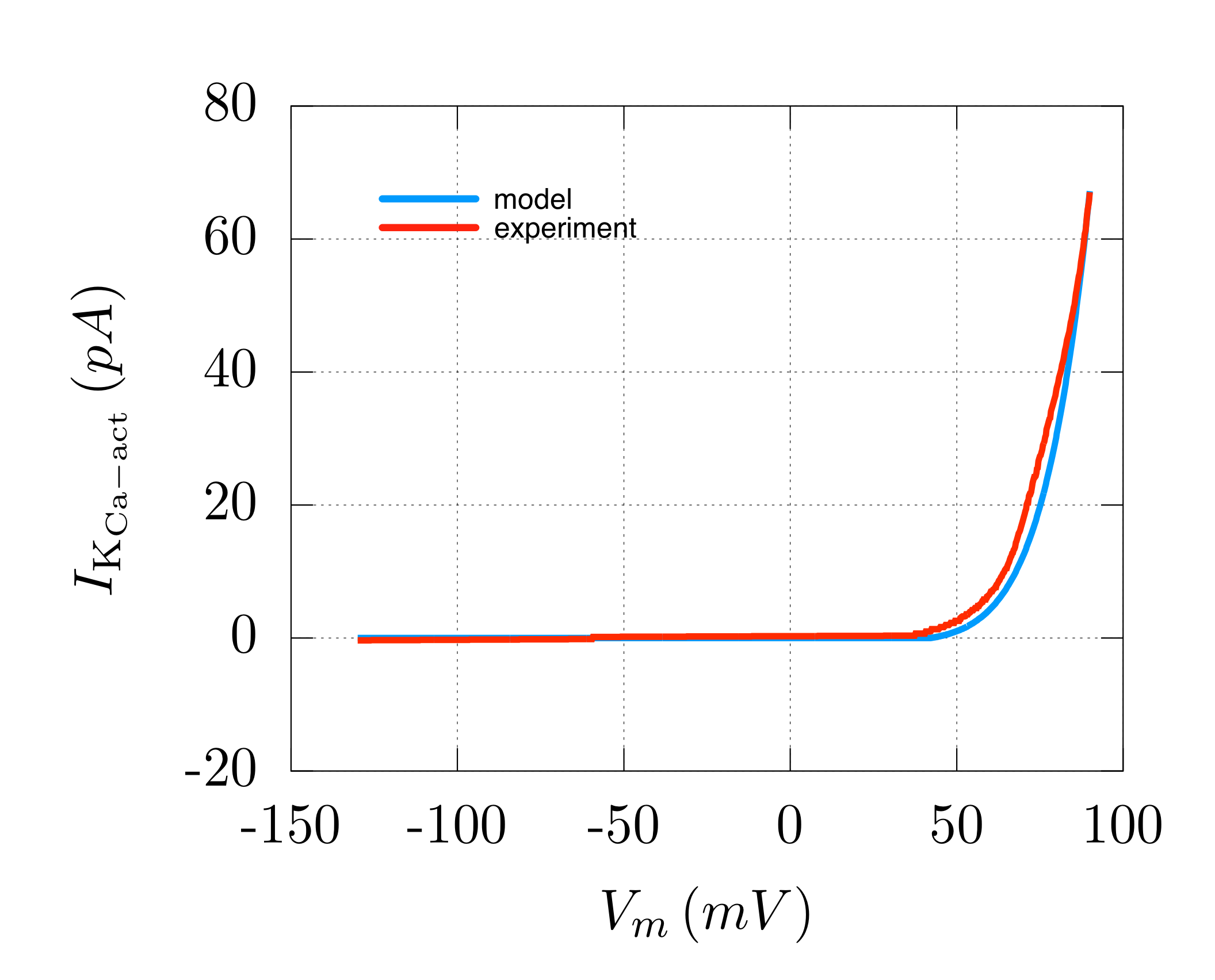
**Figure 4**

Experimental figure to be included.

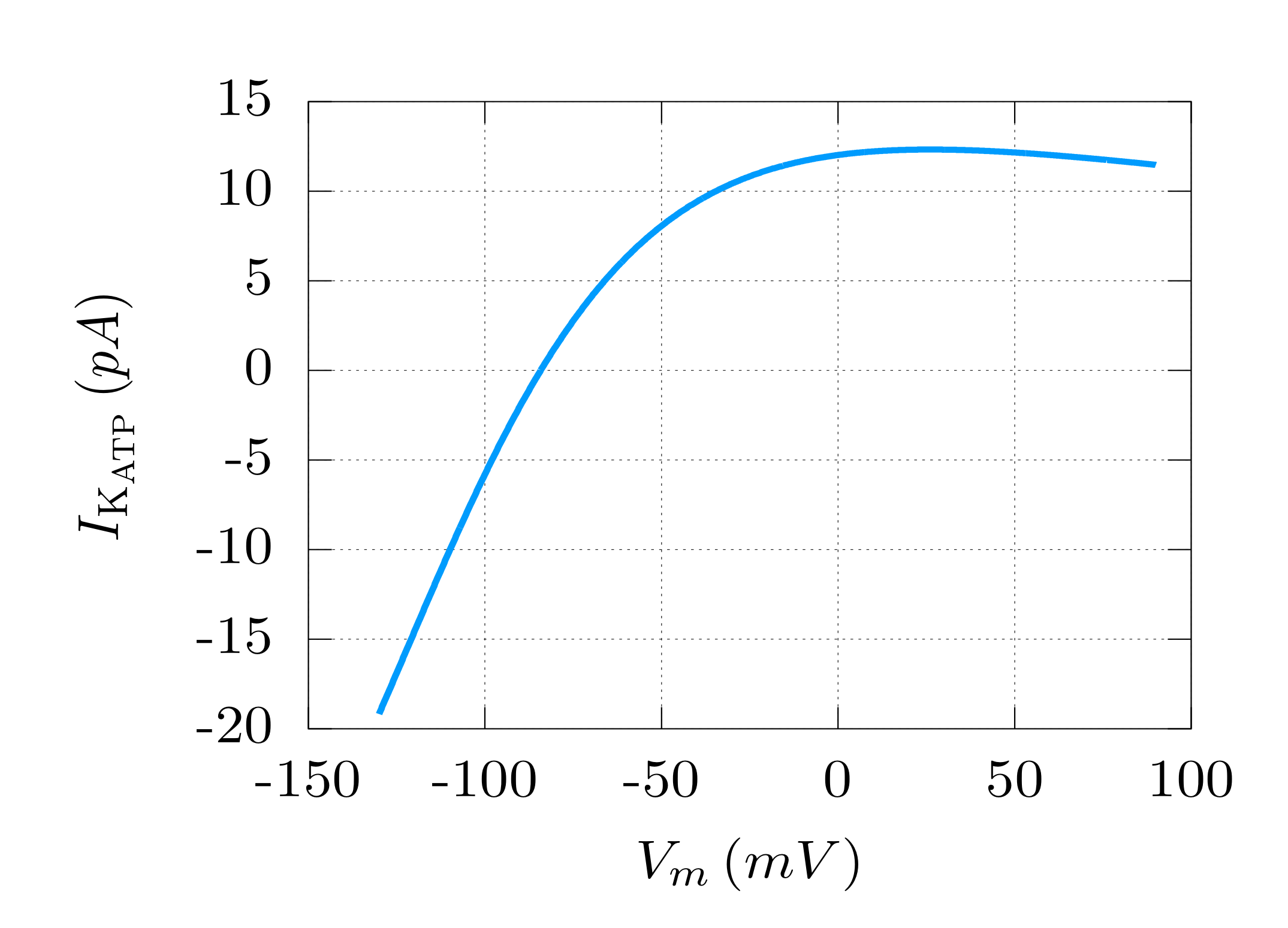
**Figure 5**

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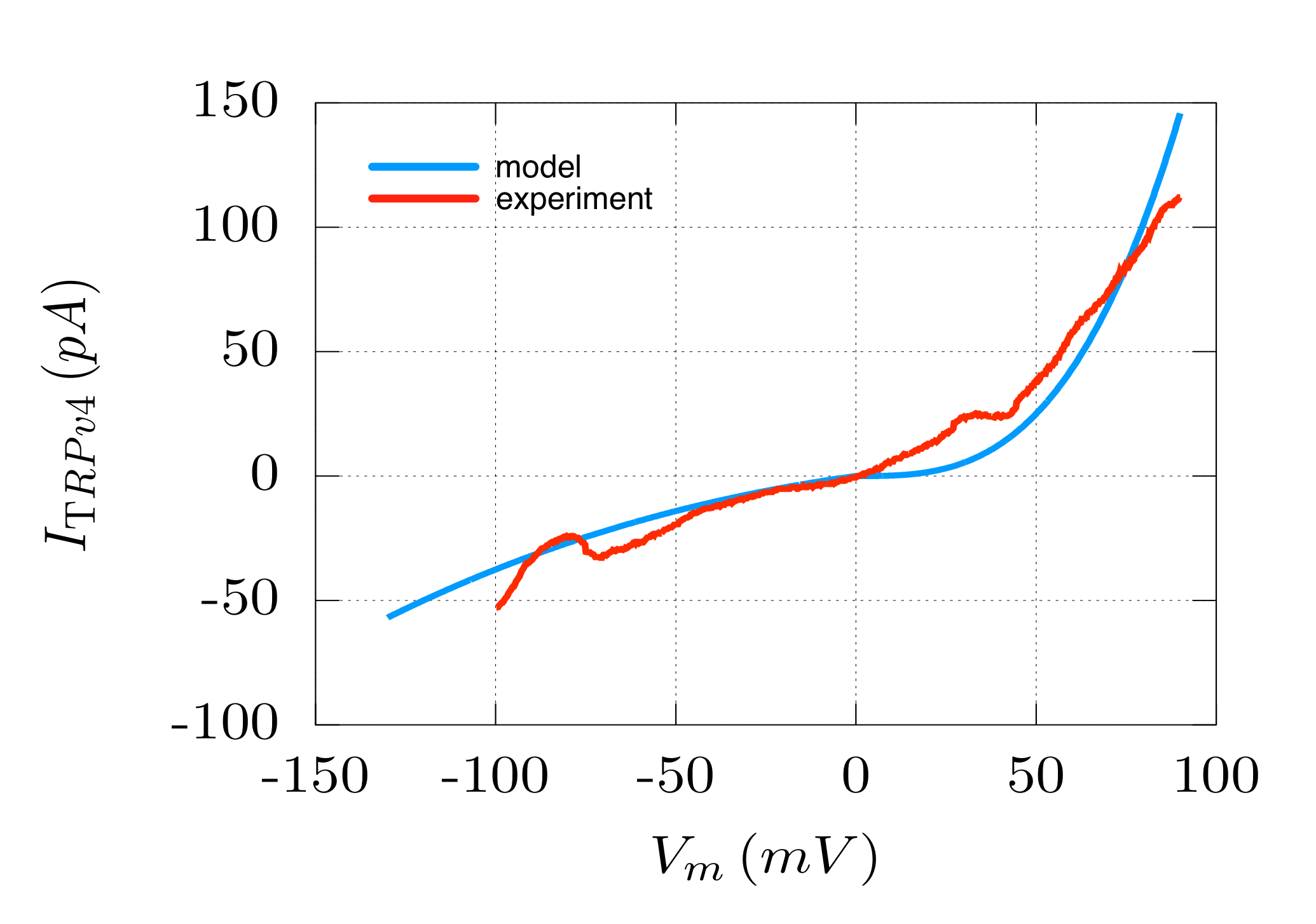
**Figure 6**

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**Figure 7**

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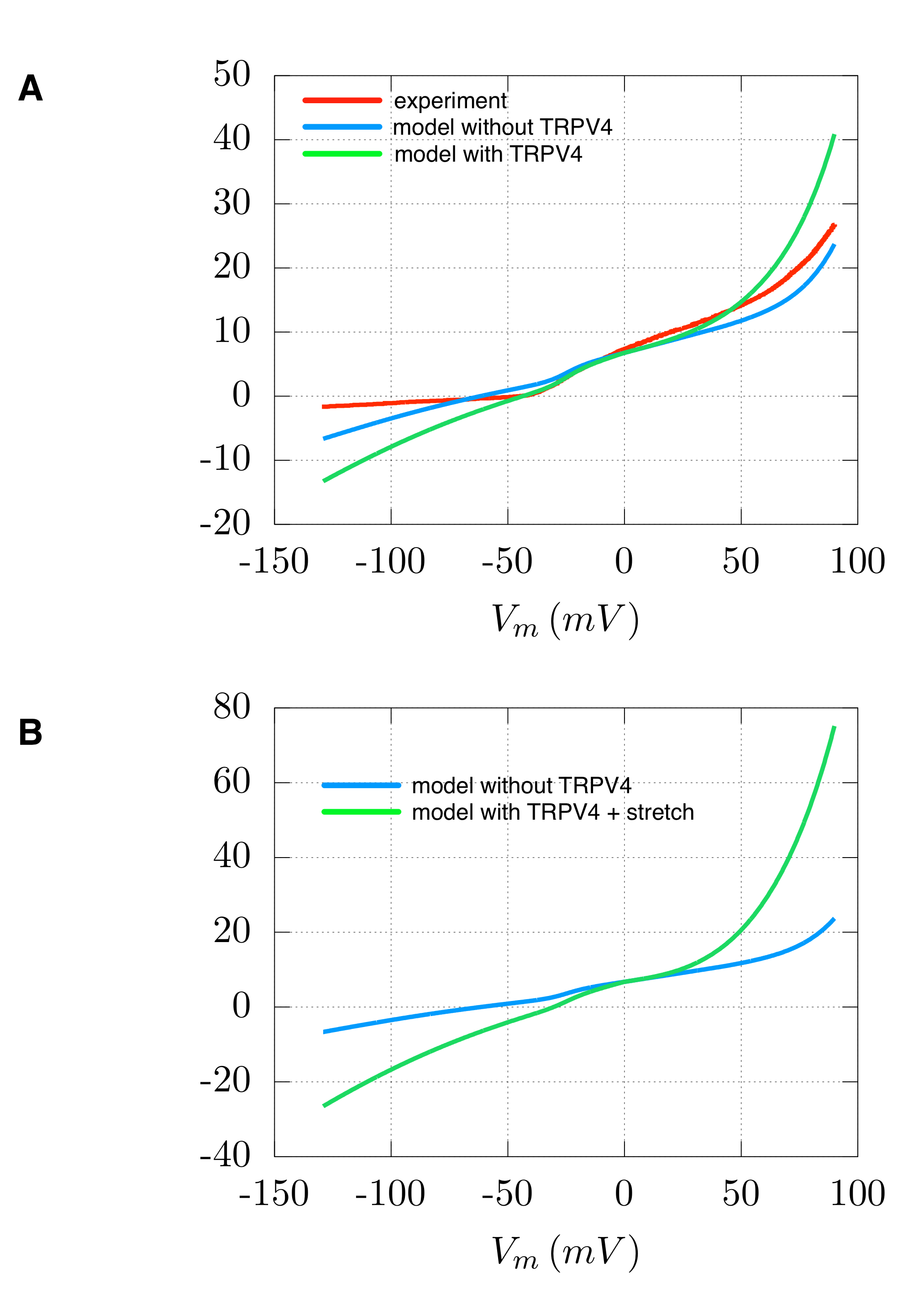
**Figure 8**

****

**Figure 9**

Whole-cell current-voltage relationship as compared to model results.

**Figure 10.**



APPENDIX:

Model of seal resistance re: membrane potential